Arnold Schwarzenegger
Governor

EMISSION REDUCTION OPPORTUNITIES FOR NON-CO_2 GREENHOUSE GASES IN CALIFORNIA

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Abstract

Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California provides an analysis of mitigation options for sources of non-CO_2 greenhouse gases, including natural gas and petroleum systems, landfills, manure management systems, electric power systems, refrigeration and air conditioning systems, and other sources. The purpose of this study is to provide the state with information on the costs and benefits of specific options for reducing greenhouse gas emissions from these sources. The results of this study are reflected in the form of marginal abatement cost curves. Costs and benefits of specific options are dependent on a variety of assumptions, including discount rates and tax rates. For this analysis, results are shown for two years (i.e., 2010 and 2020) and two discount rate/tax rate combinations (i.e., a 4% discount rate/0% tax rate; and a 20% discount rate/40% tax rate). Under the first scenario, California could mitigate up to 31.4 million metric tons of carbon dioxide equivalent (MMTCO_2 Eq.) at a break-even price of \$50/MTCO_2 Eq. in 2020. Under the 20% discount rate scenario, the state could mitigate 28.9 MMTCO_2 Eq. at a break-even price of \$50/ MMTCO_2 Eq. in 2020.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the R&D Office Technical Support Contract with ICF Consulting, contract number 500-01-006, work authorization number 47AB04, conducted by ICF Consulting. The report is entitled *Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California*. This project contributes to the PIER Environmental program.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

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Executive Summary

Introduction

This report is the first to present information on the methane (CH_4), hydrofluorcarbon (HFC), perfluorcarbon (PFC), and sulfurhexafluoride (SF_6) abatement potential in California. This study summarizes and customizes currently available information on the mitigation potential of a variety of options for reducing non-carbon dioxide (non-CO_2) greenhouse gas (GHG) emissions in California. The results of this analysis were used to generate marginal abatement cost curves (MACCs) for two years (2010 and 2020) and two discount rate/tax rate scenarios (4 percent/0 percent and 20 percent/40 percent). A total of 59 mitigation options were analyzed with respect to their technical and cost characteristics and integrated into a customized MACC model for California.

Emission reduction options were considered for the following sources of GHG emissions in California: petroleum systems, natural gas systems, landfills, manure management, electric power systems, semiconductor manufacturing, and refrigeration/air-conditioning use. Other sources of non-CO_2 gases in California were omitted because: (a) the project team focused only on technically and economically feasible mitigation actions for which sufficient cost and emission reduction information could be collected, or (b) some sources are currently being investigated by the California Air Resources Board (e.g., non-CO_2 emissions from automobiles) or by other PIER-funded projects (e.g., N_2O emissions from application of nitrogen fertilizers).

Purpose and Project Objectives

The purpose of this report is to broaden the range of options for consideration in reducing GHG emissions in California. This study considers emissions and emission reduction strategies for an array of sources that are not traditionally included in state climate plans and in so doing, expands the portfolio of options available to California. Because CO_2 emissions account for the majority of GHG emissions at the global, national, and state levels (84.5 percent in California in 1999), many of the actions being taken to address GHG in California and elsewhere are focused on sources of CO_2.

Project Outcomes and Conclusions

This study's results show that a number of cost-effective mitigation options have the potential to reduce non-CO_2 GHG emissions in California. Overall, this study analyzed 59 mitigation options in 7 source categories. The results are presented in two sections: Scenario A presents the results for a 4 percent discount rate and a 0 percent tax rate; Scenario B presents the results for a 20 percent discount rate and a 40 percent tax rate. The parameters of Scenario A were chosen to approximate the costs from a societal perspective, and Scenario B was designed to relate more to private costs. Overall, costs were lower for Scenario A, as would be expected with lower discount and tax rates. However, differences in cumulative reductions varied widely at select break-even prices.

In aggregate, options in this analysis have the potential to reduce 20.7 $MMTCO_2$ Eq. in 2010, and 31.6 $MMTCO_2$ Eq. in 2020. In comparison, the baseline emissions for the sources examined in this study[1] are projected to be 40.7 $MMTCO_2$ Eq. and 57.2 $MMTCO_2$ Eq., respectively. Thus, the potential reductions represent over half of the baseline emissions—51 percent of total emissions in 2010, and 55 percent of emissions in 2020. Landfills present the greatest opportunity for emission reductions, at 9.0 $MMTCO_2$ Eq. for 2010 and 9.7 $MMTCO_2$ Eq. in 2020. In 2010, significant reductions can also be achieved in manure management (5.8 $MMTCO_2$ Eq.) and semiconductor manufacturing (3.1 $MMTCO_2$ Eq.). In 2020, significant reductions can be achieved in semiconductor manufacturing (7.1 $MMTCO_2$ Eq.), manure management (6.2 $MMTCO_2$ Eq.), and refrigeration/air conditioning (AC) (6.2 $MMTCO_2$ Eq.). Although sizeable reductions of emissions from semiconductor manufacturing are possible, the majority of these reductions are available at greater than $20/$MTCO_2$ Eq.

For Scenario A (4 percent discount rate/0 percent tax rate), several mitigation options targeting emissions from natural gas systems, landfills, manure management, and refrigeration/AC were estimated to yield a net savings (i.e., the break-even price is less than $0) to society. In total, these options represent 5.9 $MMTCO_2$ Eq. of potential reductions in 2010, and 8.7 $MMTCO_2$ Eq. in 2020. These savings are largely possible as the result of increases in efficiency, energy savings, or energy recovery associated with implementation. Options for reducing emissions from landfills and manure management account for 86 percent of these reductions. For a break-even price of less than $20/$MTCO_2$ Eq., an additional 12.1 $MMTCO_2$ Eq. can be reduced in 2010, and 16.2 $MMTCO_2$ Eq. in 2020. Options for abating landfill emissions account for the bulk of this potential, representing 56 and 45 percent of possible reductions in 2010 and 2020, respectively. In total, by implementing all options with a break-even price of less than $20/$MTCO_2$ Eq., 18.0 $MMTCO_2$ Eq. can be reduced in 2010, and 24.9 $MMTCO_2$ Eq. in 2020. At $50/$MTCO_2$ Eq., nearly all of the options included in this analysis can be implemented. At this level, cumulative reductions of 20.6 $MMTCO_2$ Eq. in 2010 and 31.4 $MMTCO_2$ Eq. in 2020 are estimated.

For Scenario B (20 percent discount rate/40 percent tax rate), net cost savings were identified for natural gas systems, landfills, manure management, and refrigeration/AC. In total, these options represent 1.7 $MMTCO_2$ Eq. of potential reductions in 2010, and 2.1 $MMTCO_2$ Eq. in 2020. Options for reducing emissions from landfills account for the majority (70 percent and 60 percent, respectively) of these reductions. For a break-even price of less than $20/$MTCO_2$ Eq., an additional 10.8 $MMTCO_2$ Eq. can be reduced in 2010, and 13.9 $MMTCO_2$ Eq. in 2020. Once again, options for abating landfill emissions account for the bulk of this potential, representing over 58 percent and 48 percent of possible reductions in 2010 and 2020, respectively. In total, by implementing all options with break-even prices of less than $20/$MTCO_2$ Eq., 12.4 $MMTCO_2$ Eq. can be reduced in 2010, and 16.0 $MMTCO_2$ Eq. in 2020. At $50/$MTCO_2$ Eq., nearly all of the options included in this analysis can be implemented. At this

[1] Note that these baseline estimates do not represent all projected non-CO_2 GHG emissions in California; some sectors, such transportation and fertilizer, are not covered in this report. Additionally, the definition of "baseline" used in this report may cause the emissions to be overstated for some sources, as some post-2000 voluntary and regulatory reductions may not considered. Please see Section 2.1 for more information.

level, cumulative reductions of 18.6 MMTCO_2 Eq. in 2010 and 28.9 MMTCO_2 Eq. in 2020 are estimated.

Recommendations

This study's results indicate that several sources of non-CO_2 emissions in California offer significant opportunities for reducing emissions. To fully capitalize on these opportunities, the state may need to take these results one step further by conducting analyses based on additional state-specific data for sources that hold the most promise. Several of the inputs to this analysis are based on national figures that have been adjusted to reflect circumstances in California. To ensure that specific mitigation actions will deliver reductions at the costs estimated in this study, the state may want to develop or expand upon emission and cost data for specific sites or projects in California. In addition, the range of mitigation opportunities addressed in this study could be expanded to include other sources of non-CO_2 emissions. For example, inclusion of nitrous oxide emissions from fertilizer application will depend on the development of process-based models, under development in a PIER project, to predict emissions associated with various application rates and methods. This study could be expanded to evaluate the impact of alternate policy outcomes that may increase or decrease costs and benefits of specific mitigation options (e.g., impacts of net metering on manure management options). Finally, there are some new mitigation strategies for which preliminary cost and emission reduction information could be used to further reduce emissions from certain sources (e.g., use of CO_2 in stationary refrigeration equipment).

Benefits to California

This study is the first to explore the costs and benefits of GHG mitigation strategies for non-CO_2 gases in California. The evaluation of these strategies benefits California in three ways: (1) it broadens the portfolio of emission reduction activities available to state policymakers, (2) it explores the cost effectiveness of many strategies that have proven cost-effective in other states, and (3) it addresses emissions from some of the fastest growing sources in the state (e.g., semiconductor manufacturing and refrigeration/air conditioning).

1.0 Introduction

Current research has largely supported earlier scientific findings that emissions of greenhouse gases (GHGs) from human activities have been steadily increasing since the industrial revolution.[2] In addition, the United Nations-sanctioned technical body, the Intergovernmental Panel on Climate Change, reported that: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

In response to early scientific findings related to the impact of human activities on climate, the United Nations General Assembly established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change in 1990. At the United Nations Framework Convention on Climate Change held in 1992 in Rio de Janeiro, Brazil, over 180 nations adopted the agreement to reduce GHG emissions. The agreement was ratified by the United States the same year. At the 1997 Conference of the Parties in Kyoto, Japan, the protocol Kyoto Protocol was adopted to meet specific GHG emission goals.

In February 2005, the Kyoto Protocol came into force when Russia ratified it, thus meeting the requirements by which the Protocol would go into effect. As of the end of April 2005, 150 countries—representing nearly 62 percent of emissions from Annex I countries[3]—had agreed to meet the targets of the Kyoto Protocol.[4] By ratifying or accepting the treaty, these nations have pledged to cut their collective emissions by 5.2 percent by 2012. Although the United States has not ratified the Kyoto Protocol, ratification abroad indicates that GHG emission reduction strategies and technologies are going to become increasingly important in the coming years.

Recognizing of the importance of this issue and the potential impacts of climate change on the state's economy, California has undertaken a series of legislative, voluntary, and research initiatives to facilitate the reduction of GHG emissions, including:

- In September 2000, the California Legislature passed Senate Bill 1771 (SB 1771, Sher, Chapter 1018, Statutes of 2000), requiring the California Energy Commission (Energy Commission), in consultation with other state agencies, to update California's inventory of GHG emissions in January 2002 and every five years thereafter. The report, *Inventory of California Greenhouse Gas Emissions and Sinks: 1990–1999* (CEC 2002a), presented the Energy Commission's estimates of emissions and carbon sinks from 1990 to 1999. The same legislation, signed into law by then Governor Davis in October 2001, established the California Climate Action Registry. The Registry is a

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[2] For purposes of this report, greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Although the first three gases are also emitted from natural sources, this report addresses emissions due to human activities (anthropogenic emissions).

[3] Annex I countries are those industrialized nations that were members of the Organization for Economic Cooperation and Development (OECD) in 1992, as well as nations with economies in transition, that are parties to the United Nations Framework Convention on Climate Change (UNFCCC).

[4] UNFCCC (2005). Available online at http://unfccc.int/essential_background/kyoto_protocol/status_of_ratification/items/2613.php

nonprofit voluntary registry that became operational in October 2002 and currently has 44 members.

- On July 22, 2002, Governor Davis signed Assembly Bill 1493 (AB 1493, Pavley, Chapter 200, Statutes of 2002)—landmark legislation to combat climate change. This bill directs the California Air Resources Board (CARB) to adopt regulations to achieve the maximum feasible and cost-effective reduction of GHG emissions from motor vehicles. The standards proposed by the CARB address emissions of all GHGs emitted by motor vehicles, which include HFCs from motor vehicle air-conditioning in addition to carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) associated with fuel combustion.
- In September 2003, California Governor Schwarzenegger , along with the Governors of Washington and Oregon, launched the West Coast Governors' Global Warming Initiative. The Governors committed the states to acting "individually and regionally to reduce GHG emissions" through strategies that "provide long-term sustainability for the environment, protect public health, consider social equity, and expand public awareness." In November 2004, the West Coast governors reviewed and accepted a series of recommendations, most of which target CO_2 emissions.
- In 2004, California and seven other states filed a lawsuit against the nation's five largest utility companies demanding that they reduce their emissions.[5] The lawsuit states: "There is a clear scientific consensus that global warming has begun, is altering the natural world, and that global warming will accelerate in this century unless action is taken to reduce emissions of CO_2. This complaint seeks a court order requiring defendants to reduce their emissions of carbon dioxide, thereby abating their contribution to global warming, a public nuisance." The complaint alleges that, in California, global warming could: cause heat-related deaths to double in Los Angeles, with the poor and elderly at most risk; worsen smog and, as a result, increase the incidence of asthma and other respiratory diseases; produce rising sea levels, and inundate low-lying property and damage infrastructure along the state's 1,100-mile coastline; cause San Francisco to suffer a 100-year storm every 10 years; cause billions of dollars of property damage due to increased flooding; and threaten to inundate tidal marshes in the San Francisco Bay estuary, the largest on the West Coast.
- Also in 2004, the Energy Commission established a Climate Change Advisory Committee to "make recommendations to the Energy Commission on the most equitable and efficient ways to implement international and national climate change requirements based on cost, technical feasibility, and relevant information on current energy and air quality policies and activities and on GHG emissions reductions and trends since 1990." The Committee met for the first time on July 15, 2004 and has met quarterly since then.[6]

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[5] Available on the Internet at http://ag.ca.gov/newsalerts/2004/04-076.htm.

[6] For more information on the Climate Change Advisory Committee, see www.energy.ca.gov/global_climate_change/04-CCAC-1_advisory_committee/index.html.

- Finally, in June 2005, Governor Schwarzenegger announced a new plan for reducing California's GHG emissions. This plan set goals to reduce the state's emissions to 2000 levels by 2010, to 1990 levels by 2020, and to 80 percent below 1990 levels by 2050. These reduction goals were announced during the final revision process of this report, and are not reflected in the report.

In addition to these actions, the state has undertaken several research efforts to identify promising mitigation actions. This report discusses the findings of one such effort.

This report is the first to present information on the costs of reducing emissions of CH_4, hydrofluorcarbons (HFCs), perfluorcarbons (PFCs), and sulfurhexafluoride (SF_6) in California. This study analyzes currently available information on the mitigation potential of a variety of non-CO_2 emission reduction options in California. The results of this analysis were used to generate marginal abatement cost curves (MACCs) for two years (2010 and 2020) and two discount rate/tax rate scenarios (4 percent/0 percent and 20 percent/40 percent). A total of 59 mitigation options were analyzed with respect to their technical and cost characteristics and integrated into a customized MACC model for California.

Emission reduction options were considered for the following sources of GHG emissions in California: petroleum systems, natural gas systems, landfills, manure management, electric power systems, semiconductor manufacturing, and refrigeration/air-conditioning use. Readers may notice that some sources of non-CO_2 gases are absent from this report (e.g., N_2O emissions from fertilizer application). Omission of these sources reflects the project team's interest in focusing on technically and economically feasible mitigation actions for which cost information and emission reduction potential could be collected. Readers may also notice that the emission estimates are significantly lower than the estimates reported in California's GHG emissions Inventory (CEC 2002a). This difference exists because of two primary reasons: (1) CO_2 emissions, which are not included in this analysis, comprise about 85 percent of California's GHG emissions, and (2) due to the omission of some sources, explained above, nearly half (49 percent) of California's non-CO_2 emissions are not covered in this report.

2.0 Methodology

2.1. Baseline Emissions

The first step in this analysis was to determine the "baseline" emissions for each sector. Baseline emissions reflect the amount of GHGs that would be emitted from each source category if no mitigation actions are taken. The baselines are an integral part of the mitigation analysis, as potential emission reductions are estimated with respect to baseline emissions.

"Baseline emissions" for the purpose of this study were defined in consultation with the Contract Manager and others at the Commission. The methods used to estimate baseline emissions for specific sources are described in the corresponding sections of this report; however, the following parameters apply to all of the baselines generated for this study:

- **Reductions from voluntary actions implemented by the end of 2000.** Some industries have already begun to voluntarily reduce their non-CO_2 GHG emissions.

Any actions that were implemented prior to the end of 2000 are assumed to continue to reduce emissions through 2020.

- **Reductions from regulatory actions implemented by 2000.** Some national and state regulations are resulting in the reduction of GHGs from certain sources. Again, the baseline assumes that all reductions resulting from *regulations* in place by the end of 2000 will continue to reduce GHG emissions through 2020. Some of these reductions may not actually occur until after 2000, but they are included as long as the regulation itself was in place by 2000.
- **No further action beyond 2000.** The baselines used in this study do not reflect any additional mitigation actions—either voluntary or regulatory—that occur beyond 2000 (i.e., actions as a result of existing regulations are modeled; however, actions resulting from regulations promulgated after 2001 are not). For some sources, this approach may yield higher baseline emissions than reality, as some reductions may take place after 2000. This is the case for emissions from motor vehicle air conditioners, as California's "Pavley" Bill (AB 1493) was signed into law in 2002. The law will reduce GHG emissions from vehicles, including those from mobile air conditioners, and will go into effect in 2006 or later. Although reductions in emissions from motor vehicle air conditioners are likely in 2006 and beyond, these future reductions are not reflected in the baseline used in this study. Similarly, in the semiconductor sector, the U.S. companies have set a voluntary goal to reduce emissions to 10 percent below 1995 levels by 2010. Additionally, some utilities in California are currently taking voluntary steps to reduce their SF_6 emissions. Although their activities through 2000 are reflected in the current analysis, the utilities' post-2000 SF_6 mitigation actions are not presented. Taking into account these potential reductions from motor vehicle air conditioners, semiconductor manufacturing, and the electric power sector, the baseline would be reduced by 7 percent in 2010, and 14 percent in 2020. Although there may be an indication that future reductions may take place, the nature and extent of these reductions are not yet known. Consequently, this study uses 2000 as a clear cut-off point, because it is a recent year for which reliable data on emissions and mitigation activities are available and is often used as a reference year for evaluating GHG reductions and reduction targets.

The different gases examined in this report have unique characteristics that cause their impacts on global warming to be unequal. Therefore, all emissions in this report are presented in terms of CO_2 equivalent, in order to give perspective to the significance of the emissions. The gases are converted to CO_2 equivalent based on their respective global warming potentials, or GWPs, which are factors that compare the relative potency of each gas to that of CO_2. For this report, ICF used the GWPs published in the IPCC Second Assessment Report (SAR). In 2002, IPCC released a Third Assessment Report (TAR) with updated GWPs. However, international reporting guidelines still require the use of the SAR values so that previous analyses can be compared to more recent analyses. So that this report is consistent with international reporting guidelines, as well as with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–1999* (EPA 2004d), ICF has continued the convention of using the SAR GWPs. Table 1 presents the GWPs for the gases analyzed in this report.

Table 1: Global Warming Potentials of Gases Analyzed in this Report

Greenhouse Gas	Global Warming Potential (GWP)
Methane (CH_4)	21
Sulfur Hexafluoride (SF_6)	23,900
Tetrafluoromethane (CF_4)	6,500
Hexafluoroethane (C_2F_6)	9,200
Octafluoropropane (C_3F_8)	7,000
Octafluorocyclobutane (C_4F_8)	8,700
Trifluoromethane (HFC-23)	11,700
Nitrogen Trifluoride (NF_3)	8,000

2.2. Marginal Abatement Costs

The marginal abatement costs estimated in this study are presented in terms of cost per unit of emissions reduced, i.e., U.S. dollars (real year 2000 terms) per metric ton CO_2-equivalent emission reduction. Each mitigation option is associated with various costs, savings, efficiencies and other variables, described below. Using these variables, Equation 1 (below) calculates the net specific abatement cost or "break-even" price. The term break-even price refers to the price at which an entity (e.g., plant, manufacturer, utility) can be expected to be financially indifferent as to whether to institute an option. At a break-even price of zero, an entity can install a retrofit or institute an alternative gas for an amount exactly equal to the energy or other savings that would be realized; the break-even price of zero is therefore considered to represent the reductions that can be achieved with no net cost. At negative break-even prices, entities are expected to experience net savings while reducing emissions simultaneously. For these reasons, the emission reductions achievable at break-even prices equal to or less than zero are of particular interest in this report. At positive break-even prices, on the other hand, an option might only be considered worthwhile if some external value were "attached" to the emission reduction. This value might be in the form of tax relief, rebates, emission reduction credits, or other government-offered incentives.

These prices are determined through a discounted cash-flow analysis, incorporating discount rate (i.e., interest rate) and tax rate assumptions. The most representative discount and tax rates will vary by individual economic sectors; however, for the purpose of this report, ICF investigated two specific scenarios: Scenario A presents the results for a 4 percent discount rate and a 0 percent tax rate; Scenario B presents the results for a 20 percent discount rate and a 40 percent tax rate. The parameters of Scenario A were chosen to approximate the costs from a societal perspective, and Scenario B was designed to relate more to private costs.

$$\sum_{t=1}^{T}\left[\frac{(P\times ER)(1-TR)+R(1-TR)+TB}{(1+DR)^{t}}\right]=CC_{0}+\sum_{t=1}^{T}\left[\frac{RC(1-TR)}{(1+DR)^{t}}\right] \qquad \textbf{Equation 1}$$

where:
- T is the option lifetime, in years
- P is the break-even price of the option in \$/MTCO$_2$ Eq.
- ER is the annual emissions reduction achieved by the technology, in MTCO$_2$ Eq.
- TR is the tax rate
- R is the revenue generated from energy production (scaled based on regional energy prices) or savings (e.g., from the use of less expensive ODS substitutes), in 2000 U.S. dollars
- TB is the tax break equal to $CC_0/T \times TR$
- DR is the selected discount rate
- CC_0 is the capital cost of the option, in 2000 U.S. dollars
- RC is the recurring (O&M) cost of the option, in 2000 U.S. dollars

Source: (EPA 2004a)

As mentioned above, break-even prices are driven by a number of factors, including the cost of implementing and maintaining a mitigation option and the fraction of baseline emissions that can be mitigated by that option. This analysis resulted in marginal abatement costs calculated based on the variables listed below (the units used in this report are presented in parentheses). The first three characteristics (market penetration, technical applicability, and reduction efficiency) impact potential emission reductions; the higher these values, the more emissions a given option may reduce. The next four characteristics (operational lifetime, one-time capital costs, annual costs, and benefits) influence the cost of implementing an option.

- **Market Penetration (%).** *Market penetration* is the percent of emissions from a given source that are expected to be addressed by a given option. This characteristic is used to quantify the likelihood that an option will be adopted for a given source category. Although it may be technically feasible to reduce a certain percentage of baseline emissions from a given source (represented by the technical applicability), in reality, entities may choose one option over another for a variety of reasons that may include, but are not limited to, cost. For example, for landfills, the market penetration is the percent of emissions associated with a particular waste-in-place category that are mitigated by a direct gas use or electricity project. That is, of the reducible emissions associated with landfills in the category of 300,000–400,000 tons of waste-in-place, 33 percent are mitigated using a direct gas use project, and 67 percent are mitigated using an electricity project. Therefore, the market penetration for direct gas projects for the 300,000–400,000 ton category is 33 percent.
- **Technical Applicability (%).** In a given source category, some mitigation options are applicable to only a portion of the baseline emissions. For example, in the refrigeration and air conditioning source category, some options that can reduce emissions from motor vehicle air conditioners cannot be applied to stationary air conditioning equipment. The percentage of the baseline to which a mitigation option may be applied is called its *technical applicability.*
- **Reduction Efficiency (%).** Not all of the emissions to which a particular mitigation option is applied are necessarily mitigated. For example, CH_4 emissions from

manure management systems can be collected and used as an energy source; however, while the collection system may be installed to address emissions from a particular operation, a small percentage of those emissions (about 5 percent) still escape into the atmosphere (and therefore are not mitigated).

- **Operational Lifetime (yrs).** The lifespan of mitigation projects impacts the total cost of implementing an option. If a project relies on equipment that needs to be replaced every five years, its overall costs will be higher than if its equipment needs to be replaced every 20 years.
- **One-Time Capital Costs (\$/MTCO$_2$ Eq.).** One-time capital costs can also be referred to as installation costs, and reflect the initial implementation of the mitigation option (e.g., cost of purchasing and installing equipment).
- **Annual Costs (\$/MTCO$_2$ Eq.).** Most mitigation options require annual maintenance costs to cover the costs of personnel needed to operate the projects or to repair and maintain the equipment.
- **Benefits (\$/MTCO$_2$ Eq.).** Some costs may be offset by monetary savings that result from the implementation of mitigation activities. For example, using CH_4 from landfills or manure management systems may lessen the amount of electricity that a landfill or farm must purchase, reducing their electricity costs (or even provide a source of income, as landfills may sell their electricity or landfill gas).

This document reports achievable reductions and marginal abatement costs for the years 2010 and 2020. The values presented for those numbers represent the emissions that would be achieved in that year. These years were chosen by the Energy Commission for this analysis, but the results could be adapted to reflect any year, as long as the characteristics described above were revised accordingly.

3.0 Methane Emissions

Twenty-one times more potent than CO_2, methane is the greatest contributor to non-CO_2 GHG emissions in California. Methane is emitted during the production, transportation, and refining operations of petroleum and natural gas systems, and is a by-product of the anaerobic decomposition that occurs in landfills and manure management systems. Because CH_4 can be combusted and used as an energy source, many mitigation options focus on the collection and utilization of gas; other mitigation options target prevention of CH_4 emissions altogether.

3.1. Petroleum Systems

Methane is emitted during crude oil production, transportation, and refining operations. Petroleum facilities, such as offshore platforms and refineries, are highly regulated sources; consequently, a number of actions (e.g., flaring systems, vapor recovery units on storage tanks, and directed inspection and maintenance using EPA Method 21) are currently implemented to prevent the release of volatile organic compounds, including CH_4, to the atmosphere. Of the remaining emissions occurring in this sector, fugitives from sources that include storage tanks (e.g., working and breathing losses from fixed- and floating-roof tanks), and oil well head components (e.g., pumps, compressors, and valves) predominate.

3.1.1. Petroleum Systems: Baseline Emissions

The California Air Resources Board has published estimates of air emissions from petroleum systems in its 2005 Almanac Emission Projection data (CARB 2005). ICF obtained historical and projected emission estimates for 2000, 2005, 2010, 2015, and 2020 directly from this database.

The CARB database is a compilation of emission estimates reported by California's 35 local air districts. The methodologies utilized to develop these estimates vary based on the emission source, but generally use source-specific activity data and emission factors. Emission factors are derived from various references, such as the U.S. Environmental Protection Agency's (EPA's) *AP 42* (for oil production tank emissions), and the 1983 report, *Emission Characteristics of Crude Oil Production Operations in California* (for wellhead, compressor, and pump emissions). The CARB database provides district and state emission projections through 2020, with estimates based on growth only (i.e., reflects the impact of changes in petroleum infrastructure), control only (i.e., reflects the impact of future state regulatory actions), and growth and control combined scenarios. For the purposes of this analysis, the 2000 emission estimate was developed using a growth and control scenario, thereby incorporating current state and federal regulatory emission statutes. Emission projections through 2020 reflect a growth-only scenario.

The database reports emissions of total organic gases (TOG), which include all hydrocarbons, both reactive and non-reactive. CARB (2005) also provides "speciation factors" for each emission source; these factors represent the percent of TOG emissions that are methane. CARB (2005) provided 15 CH_4 speciation factors for the oil and natural gas industries, correlating with different aspects of the extraction, production, and refining processes. ICF assigned these factors to individual emission source categories based on professional judgment.

Table 2 presents the results of this analysis. Between 2000 and 2020, CH_4 emissions from petroleum systems in California are expected to fall by approximately 15 percent. This reduction is based on the assumption that policies will be implemented that require the use of cost-effective and technologically feasible actions to reduce California's future dependence on petroleum, as well as efforts to reduce air pollution emissions.

Table 2: Methane Emission Baseline for Petroleum Systems (MMTCO$_2$ Eq.)

	2000	2005	2010	2015	2020
Petroleum Systems	0.46	0.39	0.39	0.38	0.39

3.1.2. Petroleum Systems: Mitigation Options

Although flaring options are widely used and well-developed technologies, their efficiencies (i.e., effectiveness in converting CH_4 to CO_2) can vary significantly. Because gas flares are operated in uncontrolled conditions, they are exposed to wind, humidity, and temperature variations that reduce efficiency and increase variability; additionally, improper flaring practices can create unsteady combustion conditions. The mitigation option defined in Table 3 assumes the implementation of techniques (e.g., the optimization of flare burner pressure drop and exit velocities, and liquid removal systems to minimize the quantity of droplets in the feed stream) that enhance the overall efficiency of flares from 90 percent to 99 percent; consequently, an additional 10 percent of CH_4 fed to the flare can be oxidized to CO_2. Based on information obtained from CARB (2005), approximately 13 percent of petroleum sector CH_4 emissions relate to flare use. The cost information summarized in Table 3 is based on data quantified in the European Commission study *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change* (EC 2001). [7]

Table 3: Mitigation Options for Petroleum Systems

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Option for flared gas	Improve flaring efficiencies	100	13	10	66.61	2.21	-

Source: EC (2001) for cost data.

MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency
[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

3.1.3. Petroleum Systems: Results

ICF explored the costs and savings associated with the mitigation option described above under two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, tax rate TR = 0%; and (b) DR = 20%, TR = 40%. The break-even price and reductions associated with improving flaring efficiencies are displayed below for 2010 and 2020 in Table 4 through Table 7. As indicated in these tables, all emission reductions would occur at a break-even price greater than zero. Because this analysis includes a single mitigation option for petroleum systems, the data reported in the "incremental reductions" and "sum of reductions" columns of these tables are identical. In future tables, the former presents emission reductions and percent of baseline emissions for a given mitigation strategy, while the latter tallies the cumulative reductions across strategies for a given source category.

Table 4: Petroleum Systems – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/$MTCO_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		$MMTCO_2$ Eq.	% of Baseline	$MMTCO_2$ Eq.	% of Baseline
Option for flared gas	8.21	0.005	1.3	0.005	1.3

[7] This study was based on the following reports:

AEA (1998). *Options to Reduce Methane Emissions.* AEA Environment Technology by order of EC DGXI, Culham, UK, November 1998.

IEA (1997). *Methane Emissions from the Oil and Gas Industry.* IEA Greenhouse Gas R&D Programme, Report Number PH2/7, Cheltenham, UK, January 1997.

Woodhill (1994). *Methane Emissions from Oil and Gas Production in the United Kingdom.* Woodhill Engineering, Hampton, Middlesex, UK, April 1994.

Table 5: Petroleum Systems – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Option for flared gas	8.21	0.005	1.3	0.005	1.3

Table 6: Petroleum Systems – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Option for flared gas	23.00	0.005	1.3	0.005	1.3

Table 7: Petroleum Systems – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Option for flared gas	23.00	0.005	1.3	0.005	1.3

3.2. Natural Gas Systems

The natural gas system includes gas production, processing (i.e., removal of liquefiable constituents and other compounds from produced gas before injection into the transmission system), transmission (i.e., high pressure transmission of gas from production/processing facilities to distribution networks), and distribution facilities (i.e., network to facilitate transfer of high pressure gas to end user) and pipelines. Fugitives from system components associated with each of these stages are the primary contributors to baseline emissions. Fugitive sources include, compressor packing seals, valves, pumps, pipeline losses, flanges, pipe thread connections, and pneumatics.

3.2.1. Natural Gas Systems: Baseline Emissions

ICF obtained emission estimates for 2000, 2005, 2010, 2015, and 2020 directly from CARB (2005). CARB (2005) is a compilation of emission estimates reported by California's 35 local air districts. The methodologies utilized to develop these estimates vary based on the emission source, but generally use source-specific activity data and emission factors. Emission factors are derived from various references, such as the report *Unaccounted-For Gas Project*, which identifies fugitive losses from transmission sources to be 0.2 percent of total natural gas consumption. CARB (2005) provides district and state emission projections through 2020, with estimates based on growth only, control only, and growth and control combined scenarios. As with petroleum systems, ICF developed the 2000 emission estimate using a growth and control combined scenario, while emission projections through 2020 were developed using a growth-only approach.

The database reports emissions of TOG, which include all hydrocarbons, both reactive and non-reactive. CARB (2005) also provides "speciation factors" for each emission source; this factor represents the percent of TOG emissions that are CH_4. CARB (2005) provided 15 CH_4 speciation factors for the oil and natural gas industries, correlating with different aspects of the extraction, production, and refining processes. ICF assigned these factors to individual emission source categories based on professional judgment.

Table 8 presents the results of this analysis. Methane emissions from natural gas systems in California are expected to grow by approximately 21 percent between 2000 and 2020. This increase is consistent with expectations that the natural gas system infrastructure, and thus the number of emission sources, will grow through 2020.

Table 8: Methane Emission Baseline for Natural Gas Systems (MMTCO$_2$ Eq.)

	2000	2005	2010	2015	2020
Natural Gas Systems	1.81	1.89	2.00	1.89	2.19

3.2.2. Natural Gas Systems: Mitigation Options

There are a number of technologies and practices that can mitigate CH_4 emissions from natural gas systems. Table 9 highlights the available options. The percent of emissions to which each option is applicable—based on economic conditions, (i.e., market penetration), reduction efficiency, and cost data associated with each option—are based on the U.S. EPA report entitled *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21* (EPA 2003a). Reduction efficiencies and cost data included in the report are themselves based on company-specific information collected by the U.S. EPA's Natural Gas STAR Program, and presented in numerous lessons learned studies and partner-reported opportunities.[8] Since the price of natural gas varies as it passes through the natural gas system (i.e., on average the price of gas at the distribution stage is twice that at the wellhead), savings estimates calculated by ICF Consulting in EPA (2003a) are adjusted using average national prices, to account for the implementation of options within each natural gas system stage. Because California gas prices are higher than the national averages, adjustments were made using state-level data (CEC 2003b).

The technical applicability (defined in Section 2.2) was calculated using information from the natural gas systems inventory in U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (EPA 2004d). The methodology used to develop these national estimates is based on

[8] Available online at http://www.epa.gov/gasstar/resources.htm.

Methane Emissions from the Natural Gas Industry (GRI/EPA 1996), a study conducted by the Gas Research Institute and EPA. The study developed over 100 emission and activity factors to account for potential emission sources in production, processing, transmission, and distribution operations. Emission sources modeled include: reciprocating and centrifugal compressors; dehydrators; pressure relief valves; blowdown valves; pipelines; pneumatic devices; gas wells; separators; and fugitives associated with ball/gate/plug valves, flanges, and pipe thread connections. ICF calculated the technical applicability of each mitigation option based on the specific emission source to which it could be applied. For example, the processing and transmission sector accounts for approximately 50 percent of natural gas system emissions; of this total, approximately 42 percent of emissions come from reciprocating compressors. Consequently, the mitigation option aimed at reducing compressor packing seal leaks through the installation of a Static-Pac is estimated to have a technical applicability of 21 percent. For non-competing mitigation options, a market penetration of 100 percent was assumed. For those options that can be applied to the same emission source (e.g., implementation of compressed air systems or low bleed pneumatics instead of high bleed pneumatics) the market penetration was assumed to be split evenly among the available options (e.g., in this case, 50 percent for each option).

While these estimates are based on the apportionment of emissions at the national-level, the underlying assumptions, with a few exceptions, are expected to apply at the state-level as well. The exceptions to this approach relate to specific options that are enforced by air district-specific regulations or by EPA's New Source Performance Standards. CARB provides a database listing California's local air pollution control district's (APCD) and air quality management district's (AQMD) rules that regulate stationary sources,[9] as well as statewide Best Available Control Technologies (BACT).[10] For example, the Ventura AQMD adopted a rule in 1994 enforcing the recovery of emissions from glycol dehydrators (Rule 71.5); consequently, the technical applicability of mitigation options applied to dehydrator units (e.g., installation of flash tanks separators, reducing the glycol circulation rates in dehydrators) was adjusted to account for the fact that the option cannot be applied to emissions from Ventura AQMD. In keeping with the baseline definitions described in Section 2.1 above, rules or regulations enforced after 2000 (e.g., San Joaquin AQMD Rule 4408-Glycol Dehydration Systems (adopted December 19, 2002)) are not accounted for in this analysis.

Table 9 describes the cost and benefit information associated with each of 22 mitigation options.

[9] Available online at http://www.arb.ca.gov/drdb/drdb.htm.

[10] Available online at http://www.arb.ca.gov/bact/bact.htm.

Table 9: Mitigation Options for Natural Gas Systems

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
P&T-Fuel Gas Retrofit for BD Valve	Fuel gas retrofits allow the CH_4 that would be vented when compressors are taken off-line and depressurized, to be re-routed to the fuel gas system.	100	21	33	1.94	-	8.47
P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission	By reducing the circulation rate, less CH_4 is absorbed and thus less can be emitted when the glycol is regenerated.	50	< 1	30	-	0.87	8.53
P&T-D I&M (Compressor Stations)	Conduct directed inspection and maintenance using screening and measurement methods to identify and quantify leak sources.	100	4	13	0.57	1.86	8.53
Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps)	By reducing the circulation rate, less CH_4 is absorbed and thus less can be emitted when the glycol is regenerated.	50	1	31	-	1.72	8.21
Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	Replace process control pneumatic devices that are categorized as high-bleed with low-bleed devices that are designed emit lower quantities of CH_4.	50	8	86	14.01	-	8.21
P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	Replace process control pneumatic devices that are categorized as high-bleed with low-bleed devices that are designed emit lower quantities of CH_4.	50	4	86	14.01	-	8.21
P&T-Altering start-up Procedures During Maintenance	To reduce emissions during monthly maintenance of centrifugal compressors, deionized water is sprayed into the compressor while running; consequently, reducing the number of start-ups/depressurizations required per year.	100	3	100	-	-	4.47

Source: EPA (2003a).

[a] All costs and benefits are expressed in year 2000 $ per MTCO$_2$ Eq.

P&T = processing and transmission; D = distribution; Prod = production; I&M = inspection and maintenance; MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency.

Table 9: (continued)

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
D-D I&M (Distribution)	Conduct directed inspection and maintenance using screening and measurement methods to identify and quantify leak sources.	100	9	26	4.88	5.76	11.30
P&T-Installation of Flash Tank Separators Transmission & Storage)	Flash tank separators reduce the pressure of the glycol, causing the absorbed CH_4 to "flash." This CH_4 is collected and used for fuel gas or sold.	50	< 1	61	32.59	-	8.53
D-Electronic Monitoring at Large Surface Facilities	Electronic monitoring systems in distribution networks act to match system pressure with real time customer demand.	100	6	95	28.07	4.68	11.37
P&T-Recip Compressor Rod Packing (Static-Pac)	Reciprocating compressor rod packing seals leak when the compressor is shutdown but kept pressurized, Static-Pac seals create a seal around the rod, preventing fugitive losses via the packing seal vent	100	21	6	14.58	0.56	8.53
Prod-Installation of Flash Tank Separators (Production)	Flash tank separators reduce the pressure of the glycol, causing the absorbed CH_4 to "flash." This CH_4 is collected and used for fuel gas or sold.	50	3	54	100.98	-	8.21
P&T-Portable Evacuation Compressor for Pipeline Venting	During pipeline maintenance, sections of pipe may need to be depressurized. Portable evacuation compressors are used to pump-down pipeline gas to lower pressures and transfer it to another pipe.	100	3	72	318.58	2.28	8.52
Prod-Portable Evacuation Compressor for Pipeline Venting	During pipeline maintenance, sections of pipe may need to be depressurized Portable evacuation compressors are used to pump-down pipeline gas to lower pressures and transfer it to another pipe.	100	< 1	72	318.58	2.28	8.52

Source: EPA (2003a).

[a] All costs and benefits are expressed in year 2000 \$ per $MTCO_2$ Eq.

P&T = processing and transmission; D = distribution; Prod = production; I&M = inspection and maintenance; MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency.

Table 9: (continued)

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Prod-D I&M (Pipeline Leaks)	Conduct directed inspection and maintenance using screening and measurement methods to identify and quantify leak sources.	100	2	60	22.78	34.18	8.21
P&T-D I&M (Wells: Storage)	Conduct directed inspection and maintenance using screening and measurement methods to identify and quantify leak sources.	100	< 1	33	38.50	38.50	8.53
Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only)	Replace high-bleed pneumatic devices with compressed air systems.	50	8	100	6.82	62.06	8.21
P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission)	Replace high-bleed pneumatic devices with compressed air systems.	50	4	100	7.09	64.48	8.53
Prod-Installing Plunger Lift Systems in Gas Wells	When fluid accumulation occurs in a gas well, typical measures to remove this build up include venting the well. Plunger lifts can remove these liquids cost-effectively by using the well's natural energy to lift the fluids out.	100	1	4	3,985.62	159.42	8.21
P&T-D I&M (Pipeline: Transmission)	Conduct directed inspection and maintenance using screening and measurement methods to identify and quantify leak sources.	100	< 1	60	786.60	1,179.90	8.53
P&T-Surge Vessels for Station/Well Venting	Surge vessels enable this gas emitted during blowdowns to be captured for re-use as fuel or re-injection into the pipeline.	100	3	50	11,226.16	224.52	8.53
Prod-Surge Vessels for Station/Well Venting	Surge vessels enable this gas emitted during blowdowns to be captured for re-use as fuel or re-injection into the pipeline.	100	< 1	50	11,226.16	224.52	8.53

Source: EPA (2003a).

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

P&T = processing and transmission; D = distribution; Prod = production; I&M = inspection and maintenance; MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency.

ICF explored the costs and savings associated with 21 mitigation options for natural gas under the two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, tax rate TR = 0%, and (b) DR = 20%, TR = 40%. The break-even prices and reductions associated with these mitigation options are displayed below for 2010 and 2020 in Table 10 through Table 13. In 2020, California could achieve 0.511 and 0.390 $MMTCO_2$ Eq. in reductions at a break-even cost equal to or less than zero, under scenarios (a) and (b), respectively.

Table 10: Natural Gas Systems – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/$MTCO_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		$MMTCO_2$ Eq.	% of Baseline	$MMTCO_2$ Eq.	% of Baseline
P&T-Fuel Gas Retrofit for BD Valve	(8.04)	0.134	7	0.134	7
P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission	(7.65)	0.001	< 1	0.135	7
P&T-D I&M (Compressor Stations)	(6.54)	0.009	< 1	0.144	7
Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps)	(6.49)	0.002	< 1	0.146	7
Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(5.06)	0.070	4	0.216	11
P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(5.06)	0.032	2	0.248	12
P&T-Altering start-up Procedures During Maintenance	(4.47)	0.060	3	0.308	15
D-D I&M (Distribution)	(4.45)	0.048	2	0.355	18

Prod = production; P&T = processing and transmission; and D = distribution

Table 10: (continued)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
P&T-Installation of Flash Tank Separators Transmission & Storage)	(1.21)	0.002	< 1	0.358	18
D-Electronic Monitoring at Large Surface Facilities	(0.39)	0.108	5	0.466	23
P&T-Recip Compressor Rod Packing (Static-Pac)	7.20	0.025	1	0.490	25
Prod-Installation of Flash Tank Separators (Production)	14.47	0.015	1	0.505	25
P&T-Portable Evacuation Compressor for Pipeline Venting	22.40	0.042	2	0.547	27
Prod-Portable Evacuation Compressor for Pipeline Venting	22.40	< 0.001	< 1	0.548	27
Prod-D I&M (Pipeline Leaks)	31.09	0.026	1	0.573	29
P&T-D I&M (Wells: Storage)	38.62	0.002	< 1	0.575	29
Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only)	55.39	0.082	4	0.657	33
P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission)	57.54	0.037	2	0.693	35
Prod-Installing Plunger Lift Systems In Gas Wells	642.61	0.001	< 1	0.694	35
P&T-D I&M (Pipeline: Transmission)	1,348.07	0.001	< 1	0.695	35
P&T-Surge Vessels for Station/Well Venting	1,600.08	0.030	2	0.725	36
Prod-Surge Vessels for Station/Well Venting	1,600.08	< 0.001	< 1	0.725	36

Prod = production; P&T = processing and transmission; and D = distribution

Table 11: Natural Gas Systems – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
P&T-Fuel Gas Retrofit for BD Valve	(7.75)	0.147	7	0.147	7
P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission	(7.36)	0.001	< 1	0.148	7
P&T-D I&M (Compressor Stations)	(6.25)	0.010	< 1	0.158	7
Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps)	(6.21)	0.002	< 1	0.160	7
Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(4.78)	0.077	4	0.237	11
P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(4.78)	0.035	2	0.272	12
P&T-Altering start-up Procedures During Maintenance	(4.32)	0.066	3	0.337	15
D-D I&M (Distribution)	(4.06)	0.052	2	0.390	18
P&T-Installation of Flash Tank Separators Transmission & Storage)	(0.91)	0.003	< 1	0.392	18
D-Electronic Monitoring at Large Surface Facilities	0.00	0.118	5	0.511	23

Prod = production; P&T = processing and transmission; and D = distribution

Table 11: (continued)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
P&T-Recip Compressor Rod Packing (Static-Pac)	7.49	0.027	1	0.538	25
Prod-Installation of Flash Tank Separators (Production)	14.76	0.016	1	0.554	25
P&T-Portable Evacuation Compressor for Pipeline Venting	22.70	0.046	2	0.600	27
Prod-Portable Evacuation Compressor for Pipeline Venting	22.70	0.001	< 1	0.600	27
Prod-D I&M (Pipeline Leaks)	31.37	0.028	1	0.629	29
P&T-D I&M (Wells: Storage)	38.91	0.002	< 1	0.630	29
Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only)	55.67	0.090	4	0.720	33
P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission)	57.83	0.040	2	0.760	35
Prod-Installing Plunger Lift Systems In Gas Wells	642.89	0.001	< 1	0.761	35
P&T-D I&M (Pipeline: Transmission)	1,348.36	0.001	< 1	0.762	35
P&T-Surge Vessels for Station/Well Venting	1,600.37	0.033	2	0.795	36
Prod-Surge Vessels for Station/Well Venting	1,600.37	< 0.001	< 1	0.795	36

Prod = production; P&T = processing and transmission; and D = distribution

Table 12: Natural Gas Systems – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO₂ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO₂ Eq.	% of Baseline	MMTCO₂ Eq.	% of Baseline
P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission	(7.65)	0.001	< 1	0.001	< 1
P&T-Fuel Gas Retrofit for BD Valve	(7.65)	0.134	7	0.135	7
Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps)	(6.49)	0.002	< 1	0.137	7
P&T-D I&M (Compressor Stations)	(6.43)	0.009	< 1	0.146	7
P&T-Altering start-up Procedures During Maintenance	(4.47)	0.060	3	0.206	10
D-D I&M (Distribution)	(3.48)	0.048	2	0.253	13
Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(2.27)	0.070	4	0.324	16
P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(2.27)	0.032	2	0.355	18
D-Electronic Monitoring at Large Surface Facilities	5.20	0.108	5	0.463	23
P&T-Installation of Flash Tank Separators Transmission & Storage)	5.29	0.002	< 1	0.466	23

Table 12: (continued)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
P&T-Recip Compressor Rod Packing (Static-Pac)	11.48	0.025	1	0.490	25
Prod-Installation of Flash Tank Separators (Production)	34.60	0.015	1	0.505	25
Prod-D I&M (Pipeline Leaks)	35.63	0.026	1	0.531	27
P&T-D I&M (Wells: Storage)	46.29	0.002	< 1	0.532	27
Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only)	56.75	0.082	4	0.614	31
P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission)	58.95	0.037	2	0.651	33
P&T-Portable Evacuation Compressor for Pipeline Venting	93.16	0.042	2	0.693	35
Prod-Portable Evacuation Compressor for Pipeline Venting	93.16	< 0.001	< 1	0.693	35
Prod-Installing Plunger Lift Systems In Gas Wells	1,469.94	0.001	< 1	0.694	35
P&T-D I&M (Pipeline: Transmission)	1,504.87	0.001	< 1	0.695	35
P&T-Surge Vessels for Station/Well Venting	3,930.41	0.030	2	0.725	36
Prod-Surge Vessels for Station/Well Venting	3,930.41	< 0.001	< 1	0.725	36

Prod = production; P&T = processing and transmission; and D = distribution

Table 13: Natural Gas Systems – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MT$CO_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO_2 Eq.	% of Baseline	MMTCO_2 Eq.	% of Baseline
P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission	(7.36)	0.001	< 1	0.001	< 1
P&T-Fuel Gas Retrofit for BD Valve	(7.36)	0.147	7	0.148	7
Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps)	(6.21)	0.002	< 1	0.150	7
P&T-D I&M (Compressor Stations)	(6.14)	0.010	< 1	0.160	7
P&T-Altering start-up Procedures During Maintenance	(4.32)	0.066	3	0.226	10
D-D I&M (Distribution)	(3.09)	0.052	2	0.278	13
Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(1.99)	0.077	4	0.355	16
P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices	(1.99)	0.035	2	0.390	18
P&T-Installation of Flash Tank Separators Transmission & Storage)	5.58	0.003	< 1	0.392	18
D-Electronic Monitoring at Large Surface Facilities	5.60	0.118	5	0.511	23
P&T-Recip Compressor Rod Packing (Static-Pac)	11.77	0.027	1	0.538	25

Table 13: (continued)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Prod-Installation of Flash Tank Separators (Production)	34.89	0.016	1	0.554	25
Prod-D I&M (Pipeline Leaks)	35.91	0.028	1	0.582	27
P&T-D I&M (Wells: Storage)	46.58	0.002	< 1	0.584	27
Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only)	57.03	0.090	4	0.673	31
P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission)	59.25	0.040	2	0.714	33
P&T-Portable Evacuation Compressor for Pipeline Venting	93.45	0.046	2	0.760	35
Prod-Portable Evacuation Compressor for Pipeline Venting	93.45	0.001	< 1	0.760	35
Prod-Installing Plunger Lift Systems In Gas Wells	1,470.23	0.001	< 1	0.761	35
P&T-D I&M (Pipeline: Transmission)	1,505.16	0.001	< 1	0.762	35
P&T-Surge Vessels for Station/Well Venting	3,930.70	0.033	2	0.795	36
Prod-Surge Vessels for Station/Well Venting	3,930.70	< 0.001	< 1	0.795	36

Prod = production; P&T = processing and transmission; and D = distribution

3.3. Landfills

As organic materials contained in landfills decompose anaerobically, CH_4 is generated and released into the atmosphere. The California Integrated Waste Management Board (CIWMB) estimates that waste disposal in California will increase about 2 percent annually (CIWMB 2005), which will likely correspond with an increase in CH_4 production at those landfills. An increasing number of landfills are installing landfill gas collection systems that control emissions of CH_4. These systems range from a simple flare that combusts CH_4 before it is emitted into the atmosphere, to projects that collect landfill gas to be used to produce energy. Some of these projects have been installed voluntarily. Other projects have been installed in response to local air district rules which implement the requirements of the U.S. EPA's New Source Performance Standards/Emission Guidelines (NSPS/EG) for landfills (hereafter referred to as the Landfill Rule), to reduce landfill gas emissions at large landfills.[11]

3.3.1. Landfills: Baseline Emissions

ICF calculated baseline emissions for landfills based on data provided by CARB (2005). Below is a summary of the methodology used to calculate these emissions.

- **Obtained California-specific emissions data.** CARB publishes estimates of historical and projected emissions of total organic gases (TOG) (CARB 2005). ICF relied upon this database to obtain emission estimates for 2000, 2005, 2010, and 2020.

  The database provides emission estimates for two scenarios: grown and controlled (which anticipates future control measures) and grown only (which reflects only the growth in emissions and no new emission control systems). ICF used the "grown and controlled" values. ICF assumes that emissions reduced due to implementation of the Landfill Rule or local air district rules are reflected in the "grown and controlled" scenario, and that these reductions account for the difference in emissions between the two scenarios (about 2 percent).[12] Also, ICF assumes the majority of local air district rules involve implementing provisions similar to the federal Landfill Rule; although some air district rules implemented by 2000 may be stricter than the Landfill Rule, the additional emission reductions are believed to be relatively small.

- **Adjusted TOG values to include CH_4 only.** CARB (2005) "speciation factors" were applied to estimates of TOG to calculate CH_4 emissions. For landfills, CARB reports that approximately 98.6 percent of TOG emissions are CH_4.

Table 14 displays the baseline emissions for landfills based on the above steps.

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[11] 40 CFR Parts 51, 52 and 60 (May 30, 1991).

[12] For the natural gas and petroleum sectors, ICF used the "grown only" scenarios, because the "grown and controlled" scenarios for these sources are more likely to reflect regulations and voluntary actions implemented after the 2000 cut-off date.

Table 14: Methane Emission Baseline for Landfills ($MMTCO_2$ Eq.)[13]

	2000	2005	2010	2015	2020
Landfills	9.87	10.25	10.64	11.07	11.43

3.3.2. Landfills: Mitigation Options

Methane emissions from landfills can be reduced by capturing the CH_4 before it is emitted into the atmosphere. Landfills can install direct gas use projects or electricity projects with backup flare systems to recover and use CH_4. Direct gas use projects collect landfill gas and transport it directly to a nearby end user for direct use as a fuel. Electricity projects collect landfill gas and use it to generate electricity. Both project types can potentially provide a source of revenue for landfills, since the products (direct gas or electricity) can be sold.

Some landfills in this analysis already have a landfill gas project installed; however, these landfills still emit CH_4, because the systems are not 100 percent efficient in collecting and utilizing the landfill gas. Recovery systems are typically 85 percent efficient in capturing CH_4 (EPA 2004b).[14] The remaining 15 percent of landfill gas (known as "residual" emissions) cannot be further mitigated, because they are already processed within a landfill gas collection system. Ideally, this analysis would remove the residuals from the quantity of landfill gas that could be mitigated; however, sufficient data were not available to determine how much of the baseline emissions were residual emissions. Therefore, the estimated reductions presented here are overstated.[15]

The technical applicability of each mitigation option (see Table 17) is dependent on the amount of landfill gas generated by landfills in a given size category (e.g., the quantity of CH_4 that is emitted from landfills with a waste-in-place (WIP) of 300,001 to 400,000 short tons). ICF calculated these percents by apportioning the total calculated CH_4 emissions to the different size categories, based on the amount of total WIP represented by each size category. The WIP by landfill size was obtained from the California Biomass Reporting System (BFRS 2005). ICF based the apportionment using data for landfills without current control systems, because those

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[13] The baseline reflects an average annual increase of about 1 percent. The California Integrated Waste Management Board (CIWMB) estimates that waste disposal in California will increase about 2 percent annually (CIWMB 2005). The impact of landfill age, total waste-in-place, and climate on CH_4 generation potential results in these differences in growth rates for waste disposal and CH_4 emissions.

[14] System efficiency is limited by inefficient design and construction, scheduled and unscheduled system outages, and the inability to tap the entire landfill. This analysis assumes a collection efficiency of 85 percent, which may be too high but is the value used by EPA's LMOP program and in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2002.* (EPA 2004d). Despite efforts to identify a documented source for a California-specific recovery rate, none was identified during the course of this work.

[15] Baseline emissions include both residual emissions from LFGTE projects and emissions from uncontrolled landfills; however, insufficient information is available to differentiate these sources of emissions. Consequently, ICF assumed that all of the baseline can potentially be mitigated, thereby overestimating mitigation potential.

are the landfills for which additional mitigation is possible.[16] The largest category (landfills over 1,000,001 short tons WIP) contains three landfills that exceed 2.75 million short tons WIP, the threshold at which the Landfill Rule begins to apply. According to BFRS (2005), these landfills do not have gas collection systems in place, potentially because they do not meet the other criteria of the Landfill Rule (such as amount of organic gases emitted). ICF therefore assumes that these landfills could reduce emissions by installing landfill gas collection systems.

Using EPA (2004a), ICF determined the market penetration based on national averages for the percent of each landfill size category that has historically implemented a particular mitigation option. For example, of the landfills with landfill-gas-to-energy (LFGTE) projects and a WIP of 300,001 to 400,000 short tons, 33 percent have a direct gas use project, and 67 percent have an electricity project. These market penetrations are summarized in Table 17.

Project costs are driven by two main factors: (1) landfill size, and (2) landfill age—both shown in Table 15. In general, larger landfills tend to have more cost-effective projects. The larger the landfill, the greater the amount of CH_4 produced, and the greater the amount of direct gas or electricity the landfill can sell. Age affects CH_4 generation because it dictates the stage of decomposition of the WIP and rate of landfill gas generation. The information obtained from BFRS (2005) did not contain sufficient information to estimate landfill acreage or age; therefore ICF relied upon information provided by CEC (2004a). ICF calculated average acreage assuming an average landfill depth of 50 feet and a waste density of 1.667 cubic yards per ton (EPA 1997a), and estimated landfill age by dividing the 2000 WIP by the 2000 disposal rate.

Table 15: Landfill Size Category Characteristics

Landfill Category (short tons WIP)	Number of Landfills 2000[a]	Average Landfill Age (yrs)[b]	Average Landfill Acreage (acres)[b]	Total WIP Contained in All Landfills in Size Category (short tons)[a]
< 100,001	87	33	2.1	8,700,000
100,001–200,000	13	24	3.8	2,390,000
200,001–300,000	10	22	5.6	2,795,000
300,001–400,000	7	26	7.6	2,545,000
400,001–500,000	10	28	10.3	5,000,000
500,001–1,000,000	20	28	17.8	14,960,000
> 1,000,000	12	38	38.6	27,400,000

[a] BFRS (2005).

[b] Calculated using CEC (2004a).

[16] While it is possible that some landfills with current gas collection systems could further mitigate their emissions by installing additional or more efficient collection systems, such potential reductions are not considered in this analysis, due to lack of data availability.

ICF calculated the costs associated with installing and operating projects using EPA's Landfill Methane Outreach Program's (LMOP) cost model (EPA 2004g). Capital and operational/maintenance (O&M) costs are presented in Table 16. For direct gas projects, capital and O&M costs included skid-mounted filters, compressors, dehydration units, and the pipeline used to carry the gas to the project site; pipeline lengths were assumed to be one mile. For electricity projects, capital and O&M costs included gas compression/treatment, engines and generators, site work, housings, and electrical interconnect equipment.

Table 16: Landfill Capital and Operational & Maintenance (O&M) Costs

Landfill Category (short tons WIP)	Capital Cost (2000 $)	O&M Cost (2000 $)
Electricity Projects		
< 100,001	475,632	18,495
100,001–200,000	605,249	36,519
200,001–300,000	721,361	53,518
300,001–400,000	808,623	66,567
400,001–500,000	902,779	81,049
500,001–1,000,000	1,379,242	152,853
> 1,000,000	2,562,683	334,659
Direct Gas Projects		
< 100,001	429,026	13,942
100,001–200,000	471,424	25,456
200,001–300,000	507,891	36,547
300,001–400,000	539,406	45,302
400,001–500,000	580,320	55,797
500,001–1,000,000	715,031	101,959
> 1,000,000	1,059,662	221,264

Source: Calculated using EPA (2004b).

ICF then estimated potential revenue from the projects by multiplying the potential million British thermal units (MBtu) or kilowatthours (kWh) delivered by the LFGTE projects by the projected sale price of electricity at $0.045/KWhr and direct gas at $4.5/MBtu. These prices are less than existing industrial prices. ICF did not account for additional benefits such as tax credits given the uncertainty in their availability in 2010 and 2020.[17] As indicated in Table 17,

[17] This study does not incorporate the recent new tax credits that are part of Section 45 of the Internal Revenue Service (IRS) Tax Code as the projects need to be in place by December 31, 2005 (i.e., prior to the ICF 2010 and 2020 analyses). The existing tax credit provides a tax credit of $0.009/kWhr for five years,

the benefits differ across the mitigation options as the capital and O&M costs are based on a minimum gas flow throughout the project duration (i.e., the system is undersized and the landfill gas utilized is constant). Unused landfill gas is flared rather than sold. Because landfill gas flow typically varies each year and by definition, the benefits are based on total CH_4 mitigated rather than just CH_4 utilized, the benefits vary by technology (i.e., they are not a multiple of $4.5/MBtu or $0.045/KWhr). Table 17 shows the costs and savings of each mitigation option. Note that this table shows direct offsets of emissions only; indirect offsets are not included.

Table 17: Mitigation Options for Landfills

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Direct Gas Use, WIP < 100,001 short tons	Installation of a direct gas project at landfills with a WIP up to 100,000 short tons	0	14	85	152.91	4.97	9.25
Direct Gas Use, WIP 100,001–200,000 short tons	Installation of a direct gas project at landfills with a WIP between 100,001 and 200,000 short tons	0	4	85	68.57	3.70	9.18
Direct Gas Use, WIP 200,001–300,000 short tons	Installation of a direct gas project at landfills with a WIP between 200,001 and 300,000 short tons	0	4	85	47.44	3.41	9.07
Direct Gas Use, WIP 300,001–400,000 short tons	Installation of a direct gas project at landfills with a WIP between 300,001 and 400,000 short tons	33	4	85	41.74	3.51	9.36
Direct Gas Use, WIP 400,001–500,000 short tons	Installation of a direct gas project at landfills with a WIP between 400,001 and 500,000 short tons	50	8	85	37.73	3.63	9.34
Direct Gas Use, WIP 500,001–1,000,000 short tons	Installation of a direct gas project at landfills with a WIP between 500,001 and 1,000,000 short tons	29	23	85	23.09	3.29	9.34
Direct Gas Use, WIP 1,000,000+ short tons	Installation of a direct gas project at landfills with a WIP greater than 1,000,000 short tons	31	43	85	15.00	3.13	9.16
Electricity, WIP < 100,001 short tons	Installation of an electricity project at landfills with a WIP up to 100,000 short tons	100	14	85	169.53	6.59	7.81

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which does not affect the years modeled for this report.

Table 17: (continued)

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Electricity, WIP 100,001–200,000 short tons	Installation of an electricity project at landfills with a WIP between 100,001 and 200,000 short tons	100	4	85	88.04	5.31	7.76
Electricity, WIP 200,001–300,000 short tons	Installation of an electricity project at landfills with a WIP between 200,001 and 300,000 short tons	100	4	85	67.39	5.00	7.67
Electricity, WIP 300,001–400,000 short tons	Installation of an electricity project at landfills with a WIP between 300,001 and 400,000 short tons	67	4	85	62.57	5.15	7.91
Electricity, WIP 400,001–500,000 short tons	Installation of an electricity project at landfills with a WIP between 400,001 and 500,000 short tons	50	8	85	58.70	5.27	7.89
Electricity, WIP 500,001–1,000,000 short tons	Installation of an electricity project at landfills with a WIP between 500,001 and 1,000,000 short tons	71	23	85	44.54	4.94	7.90
Electricity, WIP 1,000,000+ short tons	Installation of an electricity project at landfills with a WIP greater than 1,000,000 short tons	69	43	85	36.27	4.74	7.74

MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

ICF assumes that landfill gas collection systems collect approximately 85 percent of landfill methane; thus the reduction efficiency assumed for all mitigation options is 85 percent.

3.3.3. Landfills: Results

ICF explored the costs and savings associated with each option under two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, TR = 0%, and (b) DR = 20%, TR = 40%. The break-even prices and reductions of each option are displayed below for 2010 and 2020 in Table 18 through Table 21. In 2020, California could achieve 2.44 and 1.28 $MMTCO_2$ Eq. in reductions at a break-even cost equal to or less than zero, under scenarios (a) and (b), respectively.

Table 18: Landfills – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Direct Gas Use, WIP 1,000,000+ short tons	(4.68)	1.19	11	1.19	11
Direct Gas Use, WIP 500,001–1,000,000 short tons	(3.98)	0.61	6	1.80	17
Direct Gas Use, WIP 400,001–500,000 short tons	(2.32)	0.35	3	2.15	20
Direct Gas Use, WIP 300,001–400,000 short tons	(2.10)	0.12	1	2.28	21
Direct Gas Use, WIP 200,001–300,000 short tons	(1.39)	-	0	2.28	21
Electricity, WIP 1,000,000+ short tons	0.26	2.69	25	4.96	47
Direct Gas Use, WIP 100,001–200,000 short tons	0.69	-	0	4.96	47
Electricity, WIP 500,001–1,000,000 short tons	1.04	1.51	14	6.48	61
Electricity, WIP 400,001–500,000 short tons	2.66	0.35	3	6.83	64
Electricity, WIP 300,001–400,000 short tons	2.87	0.24	2	7.07	66
Electricity, WIP 200,001–300,000 short tons	3.39	0.40	4	7.47	70
Electricity, WIP 100,001–200,000 short tons	5.47	0.34	3	7.81	73
Direct Gas Use, WIP < 100,001 short tons	9.48	-	0	7.81	73
Electricity, WIP < 100,001 short tons	14.03	1.23	12	9.04	85

Table 19: Landfills – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Direct Gas Use, WIP 1,000,000+ short tons	(4.68)	1.28	11	1.28	11
Direct Gas Use, WIP 500,001–1,000,000 short tons	(3.98)	0.65	6	1.93	17
Direct Gas Use, WIP 400,001–-500,000 short tons	(2.32)	0.38	3	2.32	20
Direct Gas Use, WIP 300,001–400,000 short tons	(2.10)	0.13	1	2.44	21
Direct Gas Use, WIP 200,001–300,000 short tons	(1.39)	-	0	2.44	21
Electricity, WIP 1,000,000+ short tons	0.26	2.89	25	5.33	47
Direct Gas Use, WIP 100,001–200,000 short tons	0.69	-	0	5.33	47
Electricity, WIP 500,001–1,000,000 short tons	1.04	1.63	14	6.96	61
Electricity, WIP 400,001–500,000 short tons	2.66	0.38	3	7.34	64
Electricity, WIP 300,001–400,000 short tons	2.87	0.26	2	7.60	66
Electricity, WIP 200,001–300,000 short tons	3.39	0.43	4	8.02	70
Electricity, WIP 100,001–200,000 short tons	5.47	0.36	3	8.39	73
Direct Gas Use, WIP < 100,001 short tons	9.48	-	0	8.39	73
Electricity, WIP < 100,001 short tons	14.03	1.32	12	9.71	85

Table 20: Landfills – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO₂ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO₂ Eq.	% of Baseline	MMTCO₂ Eq.	% of Baseline
Direct Gas Use, WIP 1,000,000+ short tons	(1.35)	1.19	11	1.19	11
Direct Gas Use, WIP 500,001–1,000,000 short tons	1.15	0.61	6	1.80	17
Direct Gas Use, WIP 400,001–500,000 short tons	6.06	0.35	3	2.15	20
Direct Gas Use, WIP 300,001–400,000 short tons	7.17	0.12	1	2.28	21
Electricity, WIP 1,000,000+ short tons	8.31	2.69	25	4.96	47
Direct Gas Use, WIP 200,001–300,000 short tons	9.15	-	0	4.96	47
Electricity, WIP 500,001–1,000,000 short tons	10.94	1.51	14	6.48	61
Electricity, WIP 400,001–500,000 short tons	15.69	0.35	3	6.83	64
Direct Gas Use, WIP 100,001–200,000 short tons	15.91	-	0	6.83	64
Electricity, WIP 300,001–400,000 short tons	16.77	0.24	2	7.07	66
Electricity, WIP 200,001–300,000 short tons	18.36	0.40	4	7.47	70
Electricity, WIP 100,001-200,000 short tons	25.02	0.34	3	7.81	73
Direct Gas Use, WIP < 100,001 short tons	43.44	-	0	7.81	73
Electricity, WIP < 100,001 short tons	51.68	1.23	12	9.04	85

Table 21: Landfills – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Direct Gas Use, WIP 1,000,000+ short tons	(1.35)	1.28	11	1.28	11
Direct Gas Use, WIP 500,001–1,000,000 short tons	1.15	0.65	6	1.93	17
Direct Gas Use, WIP 400,001–500,000 short tons	6.06	0.38	3	2.32	20
Direct Gas Use, WIP 300,001–400,000 short tons	7.17	0.13	1	2.44	21
Electricity, WIP 1,000,000+ short tons	8.31	2.89	25	5.33	47
Direct Gas Use, WIP 200,001–300,000 short tons	9.15	-	0	5.33	47
Electricity, WIP 500,001–1,000,000 short tons	10.94	1.63	14	6.96	61
Electricity, WIP 400,001–500,000 short tons	15.69	0.38	3	7.34	64
Direct Gas Use, WIP 100,001–200,000 short tons	15.91	-	0	7.34	64
Electricity, WIP 300,001–400,000 short tons	16.77	0.26	2	7.60	66
Electricity, WIP 200,001–300,000 short tons	18.36	0.43	4	8.02	70
Electricity, WIP 100,001–200,000 short tons	25.02	0.36	3	8.39	73
Direct Gas Use, WIP < 100,001 short tons	43.44	-	0	8.39	73
Electricity, WIP < 100,001 short tons	51.68	1.32	12	9.71	85

3.4. Manure Management

Animal manure is broken down in part by anaerobic bacteria under anaerobic conditions (i.e., in the absence of oxygen). One by-product of this anaerobic process is CH_4. Although CH_4 is produced by all types of manure management systems, systems that store manure generate CH_4 at a much greater rate than other systems (e.g., an open pasture). However, these manure management systems can be adjusted to help capture and reduce the CH_4 emitted to the atmosphere. Anaerobic digester systems put the manure into specially designed containers sealed from the atmosphere that capture the CH_4 and either combust it through a flare, or utilize the CH_4 for electricity generation.

3.4.1. Manure Management: Baseline Emissions

ICF calculated CH_4 emissions from manure management systems using the methodology outlined in EPA (2004c), which is based on animal population in each manure management system and average animal characteristics such as animal waste and volatile solids produced. This analysis relied on state averages for animal characteristics and distribution of manure management system types, as reported in the *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2002* (EPA 2004d) and shown in Table 22 and Table 23. Table 23 indicates the percent of the manure resulting from the animal category that is managed by a particular system. For example, 57 percent of the manure from dairy cows is managed in anaerobic lagoons.[18] Unlike other sectors, the baseline calculated for manure includes emissions from a second type of GHG —N_2O—which constitutes approximately a quarter of the manure-related emissions.[19] However, N_2O is not considered in the mitigation analyses due to lack of readily available data.

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[18] California, through a PIER project, is developing a process-based model for manure emissions, but these data are not yet available for inclusion in this analysis.

[19] The baseline includes N_2O emissions from manure management systems only, and excludes N_2O emissions from manure used for fertilizer applications.

Table 22. Animal Characteristics

Animal	Typical Animal Mass (kg)	Total Kjeldahl* Nitrogen (kg/day per source)	Max. CH_4 Gen. Potential (cubic meters)	Volatile Solids (kg/day/1,000 mass)
Dairy Cattle				
Dairy Cows	604	0.4	0.24	9.43
Dairy Heifers	476	0.3	0.17	6.82
Beef Cattle				
Feedlot Heifers	420	0.3	0.33	3.38
Feedlot Steer	420	0.3	0.33	3.31
Bulls	750	0.3	0.17	6.04
Calves	118	0.3	0.17	6.41
Beef Cows	533	0.3	0.17	6.57
Beef Replacement Heifers	420	0.3	0.17	6.98
Steer Stockers	318	0.3	0.17	7.40
Heifer Stockers	420	0.3	0.17	6.99
Swine				
Breeding Swine	198	0.2	0.48	2.60
Market Under 60 lbs	15.88	0.6	0.48	8.80
Market 60-119 lbs	40.6	0.4	0.48	5.40
Market 120-179 lbs	67.82	0.4	0.48	5.40
Market over 180 lbs	90.75	0.4	0.48	5.40
Poultry				
Layers				
Hens > 1 yr	1.8	0.8	0.39	10.80
Pullets	1.8	0.6	0.39	9.70
Chickens	1.8	0.8	0.39	10.80
Broilers	0.9	1.1	0.36	15.00
Turkeys	6.8	0.7	0.36	9.70

Source: EPA (2004a).
* Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.
Note: All values are national averages except for quantity of Volatile Solids, which are California-specific.

Table 23. California Breakdown of Manure Management System Type (%, by Animal)

	Pasture	Daily Spread	Solid Storage	Dry Lot	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Poultry Without Bedding
Dairy Cattle								
Dairy Cows	1	11	9		21	57		
Dairy Heifers				100	1			
Beef Cattle								
Feedlot Heifers				100	1.3			
Feedlot Steer				100	1.3			
Bulls				100	1.3			
Calves				100	1.3			
Beef Cows				100	1.3			
Beef Replacement Heifers				100	1.3			
Other								
Hens > 1 yr						12		88
Pullets						12		88
Chickens						12		88
Broilers	1							99
Turkeys	1							99
Swine								
Breeding Swine	10		3		8	49	30	
Market Under 60 lbs	10		3		8	49	30	
Market 60-119 lbs	10		3		8	49	30	
Market 120-179 lbs	10		3		8	49	30	
Market over 180 lbs	10		3		8	49	30	

Source: EPA (2004a).

Note: Totals for cattle may be greater than 100 percent because manure may be managed for long periods of time in multiple systems. Other totals may not sum to 100 percent, due to rounding.

ICF obtained historical animal populations from CDFA (2004). For cattle, population was available for 2000–2004; for other animals, population was available for 2000–2003. ICF then estimated future populations for each type based on national growth rates, which were based on data reported in USDA (2004), and resulted in the following: beef cow population increased 5 percent and 2 percent between 2004 and 2010, and between 2010 and 2020, respectively. For the same time period, total cattle population increased 3 percent and 2 percent, respectively. Hog populations increased 9 percent and 2 percent between 2003 and 2010, and between 2010 and 2020, respectively. During the same time period, chicken population increased 12 percent and 4 percent, and turkey population increased 12 percent and 3 percent.

Some farm operations had already begun operating digester systems by 2000; the CH_4 reductions associated with these digesters (obtained from EPA (2003b)) were removed from the baseline. Table 24 shows the results of this baseline analysis.[20]

Table 24: Emission Baseline for Manure Management Systems (MMTCO$_2$ Eq.)

	2000	2005	2010	2015	2020
Manure Management Systems	7.82	8.50	8.85	9.20	9.54

Note: The emissions reported here include N_2O emissions in addition to CH_4, since both are represented in this sector. However, only CH_4 (about 75 percent of total) can be reduced through the options analyzed in the remainder of this chapter, which considers CH_4 emissions only.

3.4.2. Manure Management: Mitigation Options

The installation of lagoon covers or plug flow digesters reduces CH_4 emissions from manure management systems by capturing emissions and utilizing them to produce heat or electricity.[21] Although this analysis includes several other types of management systems in the baseline, in general, liquid slurry systems and anaerobic lagoons offer the greatest potential for emission mitigation. Other mitigation options, such as composting of poultry manure, are not addressed as the potential reductions are believed to be relatively small. Consequently, only emissions from swine and cattle are included in the mitigation analysis; other animal types are either not represented in these manure management systems, or the unique characteristics of those other animal types precludes significant amounts of CH_4 emissions from being mitigated. However, the emissions resulting from management of manure from these animals *are* included in the baseline analysis. Table 25 shows the percent of the manure baseline that can be mitigated (i.e., calculated CH_4 emissions from liquid slurry systems or anaerobic lagoons divided by total CH_4 and N_2O emissions). Table 26 summarizes the mitigation options investigated in this study. Note that this table reflects only direct offsets of emissions; indirect offsets (e.g., avoided utility CO_2 emissions) are not included.

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[20] Emissions in some sectors analyzed in this report are more measurable than in others. For the manure sector, the analysis required the disaggregation of emissions to various manure management system types, introducing additional uncertainty to the estimates.

[21] Other strategies, such as composting, could reduce emissions even though they would not produce electricity. Such options may be less costly and technologically simpler to implement. However, they are not considered in this analysis because necessary data were not readily available.

Table 25: Percent of Manure Baseline that is Currently Managed by Liquid Slurry and Anaerobic Lagoon Management Systems

	2005	2010	2015	2020
Liquid Slurry	**11**	**10**	**10**	**10**
Anaerobic Lagoon	**59**	**59**	**59**	**59**
Dairy Cows	59	58	58	58
Swine	0	0	0	0
Total	**70**	**69**	**69**	**69**

Source: Calculated.

Table 26: Mitigation Options for Manure Management Systems

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Covered Lagoon, not including Lagoon Cost - Large Dairy	Install a cover over a manure lagoon at a large dairy operation (5,000 cows), and collect CH_4 emissions for use as an energy source (600 kW). Does not include cost of installing the lagoon itself, since it is assumed that the lagoon already exists.	70	29	95	42.22	5.12	14.27
Covered Lagoon including Lagoon Cost - Large Dairy	Install a cover over a manure lagoon at a large dairy operation (5,000 cows), and collect CH_4 emissions for use as an energy source (600 kW). Includes cost of installing the lagoon itself.	30	29	95	56.30	5.12	14.27
Plug Flow Digester - Medium Dairy*	Install a plug flow digester at a medium-sized dairy (1,900 cows), and capture the CH_4 emissions to use as an energy source (160 kW).	4	100	95	69.27	5.12	14.27
2-Stage Plug Flow Digester - Large Dairy*	Install a 2-stage plug flow digester at a large dairy (7,200 cows), and capture the CH_4 emissions to use as an energy source (1,000 kW). A two-stage plug flow system includes a 1st stage compartment at the front end of the plug flow digester that is separated from the rest of the second stage plug flow rectangular tank. The 1st stage anaerobic activity is primarily acid formation from the manure organic matter, and the 2nd stage takes these organic acids and transforms them to CH_4 and CO_2.	1	100	95	96.38	5.12	14.27

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

Table 26: (continued)

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Covered Lagoon, not including Lagoon Cost - Small Dairy	Install a cover over a manure lagoon at a small dairy operation (250 cows), and collect CH_4 emissions for use as an energy source (30 kW). Does not include cost of stalling the lagoon itself, since it is assumed that the lagoon already exists.	70	29	95	145.67	5.12	14.27
Covered Lagoon including Lagoon Cost - Small Dairy	Install a cover over a manure lagoon at a small dairy (250 cows), and collect CH_4 emissions for use as an energy source (30 kW). Includes cost of installing the lagoon itself.	30	29	95	194.09	5.12	14.27
Centralized Digester*	This system is a larger plug flow or complete mix digester that is centrally located among a number of livestock farms. Manure is scraped and collected from farms as a semi-solid slurry, and transported to the central digester where other food processing wastes may also be added. Projects are usually at least 1 MW in size, and also have a system to manage and market the digested solids leaving the digester as organic fertilizer or soil conditioner.	4	100	90	174.67	26.14	32.31

Source: Professional judgment based on experience designing California projects, except costs for centralized digester option. For this option, capital and O&M costs are from EPA (2004f).

* For these options, ICF did not differentiate between market penetration and technical applicability because they did not have sufficient information to model at this level of detail. Therefore, the values reported for market penetration are really a combination of market penetration and technical applicability; for the purposes of the analysis, technical applicability is set equal to 100 percent.

MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

For emissions from liquid/slurry systems and their associated mitigation options, ICF could not distinguish between market penetration and technical applicability because sufficient information was not available at this level of detail. These options are indicated by an asterisk (*) in Table 26. In this table, the values for market penetration for these options actually represent the product of market penetration and technical applicability. For the mathematical purposes of this analysis, technical applicability is therefore set equal to 100 percent.

The mitigation options for emissions from anaerobic lagoons differentiate by small and large dairy farms. To calculate the market penetration for the mitigation options associated with emissions from anaerobic lagoons, ICF took the percent of the emissions that can be mitigated by a given option (Table 27) (e.g., 15 percent of emissions associated with anaerobic lagoons can be mitigated by covered lagoons for large dairy farms, including lagoon cost) and divided by the total percent of emissions associated with a particular farm size (e.g., (15 + 35) percent of emissions associated with anaerobic lagoons are from large dairies). This calculation reflects the fact that anaerobic lagoon emissions occurring at large operations should not be evaluated for mitigation using a mitigation option associated with small farms.

The technical applicability is the percent of the baseline emissions from anaerobic lagoons (i.e., 59 percent as given in Table 25) times the percent of the emissions from anaerobic lagoons associated with a particular farm size (e.g., (15+35) percent for large dairies). In essence, the technical applicability represents the percent of the baseline emissions associated with anaerobic lagoons and a particular farm size.

As indicated in Table 27, manure that is currently managed in anaerobic lagoons can be mitigated using a newly installed covered lagoon or a newly installed cover to an existing lagoon. Manure that is currently managed using liquid/slurry systems can be mitigated using a complete mix digester, plug flow digester, 2-stage plug flow digester, or a centralized digester.

Efforts to reduce the air quality and water impacts from dairy farms may result in further reductions of CH_4 emissions. There are numerous ongoing preparatory activities by CARB, air districts, and water agencies in California that may impact the implementation of specific mitigation options; however, the nature and implementation schedules of these actions are unknown at this time. Regulatory initiatives beyond those in place in 2000 are not reflected in the manure management baseline, nor are they reflected in the adoption rates for individual mitigation options. For example, CARB initiatives to regulate VOC (volatile organic compounds) emissions from concentrated animal feeding operations (CAFOs) or water agency initiatives to require agricultural wastewater treatment before land spreading may impact the future market penetration of mitigation options listed above.

The savings result from reduced electricity purchases by the farmer. Because the CH_4 is captured and used as an energy source, farmers can reduce their electricity costs. The electricity retail prices range from \$0.06 to \$0.16 per kilowatthour. For this analysis, ICF assumes an electricity price of \$0.08 per kilowatthour.[22] ICF also assumes that the generators run at 93 percent of capacity.

The net metering system currently in place for dairy manure digester electricity generation allows for the farmer to connect his generator to the utility grid at one meter location, and to receive credit for any electricity generated up to that used by the farm at all the meters attributable to the dairy farm in question. Thus some power is exported into the grid at some

[22] This price is higher than the electricity price used in the landfill analysis, as this analysis considers the price that farmers would pay to use electricity, while the landfill analysis considers the price at which landfill operators could sell their electricity.

times, but the farmer can only get credit for the share that is used by the farm. Therefore, the cost savings to farmers is limited to their reduced electricity costs and does not consider scenarios where farmers could sell their excess electricity to the grid. This analysis assumes that all potential electricity generated by these mitigation options is used on the farm to offset electricity needs.[23] This assumption will overstate the benefits to the dairy farms that are not able to use all the electricity generated by the digester electricity generation system.

Table 27: Emissions Resulting from Existing Manure Management System for which Mitigation Option is Applicable (%)

Mitigation Option	Existing System: Liquid/Slurry (%)	Existing System: Anaerobic Lagoon (%)
Covered Lagoon (including Lagoon Cost) - Large Dairy	0	15
Covered Lagoon (not including Lagoon Cost) - Large Dairy	0	35
Covered Lagoon (including Lagoon Cost) - Small Dairy	0	15
Covered Lagoon (not including Lagoon Cost) - Small Dairy	0	35
Complete Mix Digester - Medium Dairy	15	0
Plug Flow Digester - Medium Dairy	35	0
2-Stage Plug Flow Digester - Large Dairy	10	0
Centralized Digester	40	0

Source: Professional judgment.

The net metering law is in place until the end of 2005, and is expected to be extended beyond 2005, according to discussions with the Western United Dairymen's legislative representative. Also to be included in the extension are more favorable electrical rates for the avoided power, equal to the full retail rate paid by the farmer. Costs of implementing each mitigation option include the costs associated with installing the lagoon cover and digester, as well as the annual operational and maintenance (O&M) costs of running the systems. For the lagoon options, ICF separately calculated the costs for lagoon cover and collection system only, as well as lagoon cover/collection system and the installation of the lagoon itself. The data is presented in this way so that readers can distinguish the costs associated with installing an entire lagoon system from the costs associated with modifying an existing lagoon. Capital costs include the installation of the systems including the lagoon construction; the cover material and installation; the gas handling including pipeline, water and hydrogen sulfide scrubbing and gas blowers; the engine-generator and installation including the electrical interconnection and housing for the generator; the engineering design and permits required for the project; the purchase and installation of electricity meters; and other costs associated with complying with emission regulations. Operational and maintenance costs include the labor and materials for maintaining

[23] Note that if farmers cannot use all their electricity potential, they could still reduce GHGs by using the mitigation systems to flare CH_4 and not generate electricity. However, this analysis assumes the farms use the full electricity potential.

the mechanical equipment; engine maintenance and routine overhauls, gas scrubber maintenance and other moving part equipment maintenance and repairs. These costs are illustrated in Table 28 and are based on the costs for ongoing projects in California (e.g., Straus Dairy, Joseph Gallo Dairy, and Cal Poly Dairy) as well as the use of FarmWare (EPA 1997b). ICF did not account for the federal tax credit (Section 45 of the Internal Revenue Service (IRS) Tax Code) that provides a tax credit of $0.009/kilowatt-hr for five years for projects implemented by December 31, 2005, because the credit is not applicable to the years of the ICF analyses (i.e., 2010 and 2020).

Table 28: Capital and Operational & Maintenance (O&M) Costs for Manure Management Systems (2000 $ per system)

Manure Management System	Capital Cost (2000 $)	O&M Cost (2000 $)
Covered Lagoon (including Lagoon Cost) - Large Dairy	1,600,000	145,539
Covered Lagoon (not including Lagoon Cost) - Large Dairy	1,200,000	145,539
Covered Lagoon (including Lagoon Cost) - Small Dairy	275,800	7,200
Covered Lagoon (not including Lagoon Cost) - Small Dairy	207,000	7,200
Complete Mix Digester - Medium Dairy	582,000	24,000
Plug Flow Digester - Medium Dairy	525,000	38,400
2-Stage Plug Flow Digester - Large Dairy	4,565,000	240,000
Centralized Digester[a]	5,059,764	757,103

[a] For centralized digesters, the farmer also receives revenue from the sale of digestate, estimated to be $25 per metric ton of dried digestate and digestate production of 20,000 metric tons of dried digestate. However, as ICF understands, the pilot project currently being conducted by Inland Empire Utility Agency is considering a redesign. Based on professional judgment, the capital costs for the redesign are estimated to be approximately $4 million and the O&M costs are $0.24 million for a 1,000 kW system. Digestate sales are uncertain, and an estimate of $15 per metric ton of dried digestate should likely be used with digestate at approximately 5,400 tons per year. Upon finalization of the redesign, updated costs should be used in future analyses.

3.4.3. Manure Management: Results

ICF investigated the costs and savings associated with each mitigation option under the two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, TR = 0%, and (b) DR = 20%, TR = 40%. Table 29 through Table 32 illustrate the break-even prices and reductions associated with these mitigation options for years 2010 and 2020. In 2020, California could achieve 2.99 $MMTCO_2$ Eq. in reductions at a break-even cost equal to or less than zero, under scenario (a). Under scenario (b), all reductions in 2020 occur above a break-even price of zero.

Table 29: Manure Management – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Covered Lagoon, not including Lagoon - Large Dairy	(3.94)	1.73	20	1.73	20
Covered Lagoon including Lagoon Cost - Large Dairy	(2.21)	0.74	8	2.48	28
Plug Flow Digester - Medium Dairy	(0.61)	0.31	3	2.79	31
2-Stage Plug Flow Digester - Large Dairy	2.73	0.09	1	2.87	32
Complete Mix Digester - Medium Dairy	6.00	0.13	1	3.01	34
Covered Lagoon, not including Lagoon Cost - Small Dairy	8.81	1.73	20	4.74	54
Centralized Digester	9.54	0.33	4	5.07	57
Covered Lagoon including Lagoon Cost - Small Dairy	14.78	0.74	8	5.82	66

Table 30: Manure Management – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Covered Lagoon, not including Lagoon - Large Dairy	(3.94)	1.86	19	1.86	19
Covered Lagoon including Lagoon Cost - Large Dairy	(2.21)	0.80	8	2.66	28
Plug Flow Digester - Medium Dairy	(0.61)	0.33	3	2.99	31
2-Stage Plug Flow Digester - Large Dairy	2.73	0.09	1	3.08	32
Complete Mix Digester - Medium Dairy	6.00	0.14	1	3.22	34
Covered Lagoon, not including Lagoon Cost - Small Dairy	8.81	1.86	19	5.08	53
Centralized Digester	9.54	0.36	4	5.44	57
Covered Lagoon including Lagoon Cost - Small Dairy	14.78	0.80	8	6.24	65

Table 31: Manure Management – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Covered Lagoon, not including Lagoon - Large Dairy	4.82	1.73	20	1.73	20
Covered Lagoon including Lagoon Cost - Large Dairy	9.48	0.74	8	2.48	28
Plug Flow Digester - Medium Dairy	13.77	0.31	3	2.79	31
2-Stage Plug Flow Digester - Large Dairy	22.74	0.09	1	2.87	32
Complete Mix Digester - Medium Dairy	31.50	0.13	1	3.01	34
Covered Lagoon, not including Lagoon Cost - Small Dairy	39.05	1.73	20	4.74	54
Centralized Digester	48.33	0.33	4	5.07	57
Covered Lagoon including Lagoon Cost - Small Dairy	55.07	0.74	8	5.82	66

Table 32: Manure Management – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO₂ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO₂ Eq.	% of Baseline	MMTCO₂ Eq.	% of Baseline
Covered Lagoon, not including Lagoon - Large Dairy	4.82	1.86	19	1.86	19
Covered Lagoon including Lagoon Cost - Large Dairy	9.48	0.80	8	2.66	28
Plug Flow Digester - Medium Dairy	13.77	0.33	3	2.99	31
2-Stage Plug Flow Digester - Large Dairy	22.74	0.09	1	3.08	32
Complete Mix Digester - Medium Dairy	31.50	0.14	1	3.22	34
Covered Lagoon, not including Lagoon Cost - Small Dairy	39.05	1.86	19	5.08	53
Centralized Digester	48.33	0.36	4	5.44	57
Covered Lagoon including Lagoon Cost - Small Dairy	55.07	0.80	8	6.24	65

4.0 High-GWP Gas Emissions

A series of high-GWP gases are characterized as having a climate impact ranging from 210 to almost 24,000 times that of CO_2 when compared over a 100-year time horizon. These gases result from a number of commercial and industrial activities and applications. Those with significant presence in the State of California are electric power systems and semiconductor manufacture. This report includes emissions of the following high-GWP gases: Sulfur hexafluoride (SF_6), Tetrafluoromethane (CF_4), Hexafluoroethane (C_2F_6), Octafluoropropane (C_3F_8), Octafluorocyclobutane (C_4F_8), Trifluoromethane (HFC-23), and Nitrogen Trifluoride (NF_3).

4.1. Electric Power Systems

Due to its extremely stable molecular structure, SF_6 is considered an invaluable chemical for electric power systems. It has strong insulation properties, high dielectric strength, and potent arc-quenching abilities; consequently, it is used in a variety of electrical equipment, such as gas-insulated substations, circuit breakers, and switchgear. Approximately, 80 percent of all global sales of SF_6 go to electric utilities and electrical equipment manufacturers (Smythe 2004).

Under ideal conditions, SF_6 would remain contained within transmission equipment. However, in reality, SF_6 is inadvertently emitted into the atmosphere during various stages of the equipment's life cycle. For example, as equipment ages or the frequency of its use increases (e.g., in the number of circuit breaker operations), there can be an increase in the number and size of leaks (e.g., at the porcelain bushing end cap and/or between the bushing and the base mounting flange on circuit breakers). Additionally, SF_6 can be released at the time of equipment installation, servicing, or decommissioning.

4.1.1. Electric Power Systems: Baseline Emissions

Sulfur hexafluoride emission estimates for 2000 were developed using company-specific data and extrapolations based on miles of transmission lines in California. ICF obtained company-specific data from Pacific Gas & Electric (PG&E) and Southern California Edison (SCE). Both companies are members of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems, and consequently, prepare annual SF_6 emissions inventories using a mass balance approach in which all uses of SF_6 are accounted (e.g., beginning and end of year SF_6 cylinder inventories, gas-insulated equipment purchases and retirements, SF_6 sent offsite for recycling or to destruction facilities, SF_6 sold to other entities). The SF_6 data from PG&E and SCE was obtained specifically for this project, and is independent of their submissions to EPA's SF_6 Emission Reduction Partnership.

Transmission mileage is assumed to have a strong correlation with SF_6 emissions since most SF_6-containing equipment is used in high voltage transmission. Pacific Gas & Electric and SCE account for approximately 75 percent of the total electric transmission mileage in California (CEC 2004b). Transmission mileage was used to scale the combined emissions from these two companies up to reflect statewide emissions. Although both companies are members of EPA's SF_6 Emission Reduction Partnership and are consequently implementing activities to reduce SF_6 emissions, the baseline emissions do not reflect any additional voluntary or regulatory actions implemented after 2000. Additionally, ICF assumed that SF_6 emissions will grow at a rate of 2.5 percent per year through 2020, based on forecasted state electricity consumption growth in the CEC *2002-2012 Electricity Outlook Report* (CEC 2002b). Increasing electricity consumption is assumed to require more basic infrastructure (e.g., circuit breakers, transformers, sub stations) to pass on the electricity. Table 33 shows the SF_6 baseline emissions for electric power systems.

Table 33: Sulfur Hexafluoride Emission Baseline for Electric Power Systems ($MMTCO_2$ Eq.)

	2000	2005	2010	2015	2020
Electric Power Systems	0.92	1.04	1.18	1.33	1.51

In their capacity as partners in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems, both PG&E and SCE are actively undertaking steps to reduce SF_6 emissions from utility operations. Although activities through 2000 are represented in the current baseline (i.e., Table 33), emission reductions have been reported by both companies through 2003 (EPA undated; Salinas 2004). Both companies have set emission reduction goals. Southern California

Edison's goal is to reduce emissions by 45 percent from its 1999 emissions over a five-year span; SCE estimates that it came close to this target with a 40 percent reduction (H. Gollay, SCE. pers. comm.). Additionally, PG&E has set an emission reduction goal such that their 2007 emissions will be 60 percent lower than their 1998 baseline (EPA undated). To estimate the potential reduction in the emissions baseline if both PG&E and SCE's continuing SF_6 mitigation actions are accounted, it was assumed that: (1) PG&E's 2007 voluntary emission reduction goal is achieved and that the estimated annual rate of reduction between their reported 2003 emissions and 2007 target is maintained through 2020; (2) between 1999 and 2004, SCE reduced its emissions by 40 percent; beyond 2004, its annual percent reductions are similar to those experienced by PG&E ; and (3) other California utilities that are not in EPA's SF_6 Emission Reduction Partnership are not undertaking SF_6 mitigation steps; consequently, their emissions will grow at a rate of 2.5 percent per year from 2000 through 2020. Based on this approach, the electric power systems baseline will be 32 percent and 42 percent lower than current baseline estimates in 2010 and 2020, respectively.

4.1.2. Electric Power Systems: Mitigation Options

Component leakage and releases during routine maintenance and equipment installation and removal operations are the primary sources for SF_6 emissions. The mitigation option defined in Table 34 assumes the implementation of SF_6 leak detection (e.g., infrared imaging systems), leak repair, and recycling (i.e., utilizing SF_6 recycling gas carts to withdraw, clean, and return SF_6 gas to the gas-insulated equipment) activities. Leak detection and recycling systems are well developed technologies, and are considered a basic option for conservative gas handling practices. For this option, ICF assumed a market penetration of 100 percent, and that all emissions can be effectively abated. The cost information summarized in Table 34 is based on data quantified in the European Commission study Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change (EC 2001). Annual costs cited by EC (2001) incorporate the cost of labor minus the value of recovered SF_6 gas.

Table 34: Mitigation Options for Electric Power Systems

Name	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Leak Reduction and Recovery	Leak detection, repair and recycling	100	100	100	10.96	1.81	-

Source: EC (2001).

MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

4.1.3. Electric Power Systems: Results

ICF investigated the costs and savings associated with the mitigation option for electric power systems under the two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, TR = 0%, and (b) DR = 20%, TR = 40%. Table 35 through Table 38 illustrate the break-even prices and reductions associated with the mitigation option for years 2010 and 2020. All reductions would occur at a break-even price greater than zero.

Table 35: Electric Power Systems – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Leak Reduction and Recovery	3.16	1.18	100	1.18	100

Table 36: Electric Power Systems – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Leak Reduction and Recovery	3.16	1.51	100	1.51	100

Table 37: Electric Power Systems – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Leak Reduction and Recovery	5.43	1.18	100	1.18	100

Table 38: Electric Power Systems – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Leak Reduction and Recovery	5.43	1.51	100	1.51	100

4.2. Semiconductor Manufacture

A number of high-GWP gases are used and emitted as a result of two integral processes involved in semiconductor manufacturing: etching circuitry features on silicon wafers, and cleaning chemical vapor deposition (manufacturing tool) chambers. The fluorinated gases most often used in these processes include trifluoromethane (HFC-23), perfluoromethane (CF_4), perfluoroethane (C_2F_6), and SF_6. These gases have GWPs that are 11,700, 6,500, 9,200, and 23,900 times that of CO_2, respectively. Other compounds such as nitrogen trifluoride (NF_3), perfluoropropane (C_3F_8) and perfluorocyclobutane (C-C_4F_8) are also, but less commonly, used.

Semiconductor manufacture involves a step called *plasma etching,* during which reactive gases or chemicals are used to create patterns on a silicon wafer's surface. During chemical vapor deposition (CVD) chamber cleaning, gases pass through the chambers in order to volatilize residue build-up. During both of these two processes, a significant portion of the gases used are released to the atmosphere.

4.2.1. Semiconductor Manufacture: Baseline Emissions

ICF estimated baseline emissions from semiconductor manufacture in California based on a combination of U.S. Inventory figures (EPA 2004d), recently published global semiconductor manufacturing industry production shift forecasts, and an analysis of California's share of U.S. shipments of semiconductor and related device manufacturing.

Historical (1990 through 2000) emissions from semiconductor manufacturing in the United States were obtained from the U.S. Inventory (EPA 2004d). These are based in large part on figures reported to EPA through the voluntary PFC Reduction/Climate Partnership for the Semiconductor Industry. For those national emissions not accounted for by partners, EPA uses a model to estimate emissions by incorporating activity data (i.e., silicon consumption) and applying developed emission factors.

Future national PFC emissions from semiconductor manufacturing were obtained from Bartos et al. (2004), in which emission factors and projected world silicon consumption were used to estimate uncontrolled global emissions levels and apportioned among world regions based on forecasts of capital expenditures made in the industry. The published scenario chosen for the current analysis incorporates the expectation that future industry investment to add manufacturing capacity will largely occur in areas outside the United States. Because U.S. emission projections were only available from this report through 2010, later years were extrapolated using the 1990 through 2010 series. ICF derived U.S. emissions for 2015 and 2020 by calculating the least squares fit through the available time series using an exponential curve. The resulting curve was justified by an R^2 (i.e., goodness of fit) value of 0.99.

ICF estimated California's share of U.S. emissions by assuming that the current (2002) share of semiconductor manufacturing attributable to fabrication facilities (fabs) in California would remain constant through 2020. ICF estimated emissions attributable to California by comparing the ratio of manufacturing in California to that in the United States as a whole (Census Bureau 2005), expressed in terms of total value of shipments. Based on this analysis, California's share of national manufacturing was estimated to be 16 percent of the U.S. total. The U.S. emission estimates were scaled by this factor to reflect California's share of national emissions.

Table 39 presents the results of the baseline analysis.

Table 39: PFC Emission Baseline for Semiconductor Manufacture ($MMTCO_2$ Eq.)

	2000	2005	2010	2015	2020
Semiconductor Manufacture	1.03	2.00	3.36	4.95	7.74

The U.S. semiconductor industry, through its participation in EPA's PFC Reduction/Climate Partnership and the World Semiconductor Council (WSC), have set an aggressive goal to reduce PFC emissions to levels 10 percent below their 1995 industry baseline by year-end 2010. The reduction goal, though voluntary, binds each member association to an aggregate reduction.

Assuming that: (1) the WSC goal is met by 2010, (2) 2010 levels remain sustainable and constant through 2020, and (3) semiconductor industry associate (SIA) reductions are achieved equitably through the participation of all member companies and fabs (each responsible for a share of the reduction commitment as determined by each fab's share of SIA production levels), 2010 and 2020 PFC emissions resulting from semiconductor manufacturing in California are both estimated to be 0.72 $MMTCO_2$ Eq. This represents emissions 78 percent below those estimated under the no-further-action baseline scenario in 2010 and 91 percent below 2020 estimates.

4.2.2. Semiconductor Manufacture: Mitigation Options

As described above, emissions result from plasma etching (roughly 40 percent of baseline emissions) and chamber cleaning processes (roughly 60 percent of baseline emissions) (EPA 2001). Of those five technologies or practices available to mitigate PFC emissions from semiconductor manufacture, one is applicable to both sources of emissions, representing facility-wide capture and recovery of PFC gases. Three technologies have the capacity to reduce emissions resulting from etch processes (thermal destruction as well as both plasma and thermal abatement), while one option applies only to CVD chamber cleaning process emissions (Remote Clean).

IEA (2003) and EPA (2001) provided information on the variables that determine the break-even price of the five mitigation options presented in this section. These variables include financial inputs such as annual operation and maintenance costs incurred through operating fabs with mitigation options installed, and capital (or investment) costs incurred to install or implement the options. Other variables that affect the break-even price include inputs that determine the achievable emission reduction: market penetration (the share of fabs expected to adopt a particular technology or practice), technical applicability (the share of fab-wide or process-specific emissions to which a particular technology or practice is applicable), and reduction efficiency (indicating the performance factor or degree to which a technology effectively mitigates emissions).

Table 40 presents the five mitigation options included in this analysis.

Table 40: Mitigation Options for Semiconductor Manufacture

Option	Description	MP (%)	TA (%)	RE (%)	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Plasma Abatement (etch)	Isolates the etch tool from the fab's waste stream and dissociates the fluorinated compound molecules.	55	40	97	50.81	1.45	-
Remote Clean	Removes emissions from the dielectric chamber by using an upstream device that dissociates NF_3 using argon gas.	90	60	90	90.76	-	-
Catalytic Abatement	Dilutes the gas stream prior to feeding it though the scrubber.	20	40	98	67.35	5.32	-
Capture/Recovery (Membrane)	Separates unreacted and/or process-generated fluorinated compounds from other gases for further processing.	8	100	90	40.52	13.20	-
Thermal Destruction	Reduces emissions from the etching and CVD chamber cleaning process.	20	40	90	93.39	8.98	-

MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

4.2.3. Semiconductor Manufacture: Results

Using the information presented in Table 40 above, ICF developed results under the two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, TR = 0%, and (b) DR = 20%, TR = 40%. The break-even prices and reductions associated with the mitigation options are presented in Table 41 through Table 44 for years 2010 and 2020. All reductions would occur at a break-even price greater than zero.

Table 41: Semiconductor Manufacture – Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/$MTCO_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		$MMTCO_2$ Eq.	% of Baseline	$MMTCO_2$ Eq.	% of Baseline
Plasma Abatement (etch)	12.86	0.72	21	0.72	21
Remote Clean	20.39	1.64	49	2.35	70
Catalytic Abatement	20.45	0.26	8	2.62	78
Capture/Recovery (Membrane)	22.30	0.24	7	2.86	85
Thermal Destruction	29.96	0.24	7	3.10	92

Table 42: Semiconductor Manufacture – Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Plasma Abatement (etch)	12.86	1.65	21	1.65	21
Remote Clean	20.39	3.76	49	5.42	70
Catalytic Abatement	20.45	0.61	8	6.02	78
Capture/Recovery (Membrane)	22.30	0.56	7	6.58	85
Thermal Destruction	29.96	0.56	7	7.14	92

Table 43: Semiconductor Manufacture – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Plasma Abatement (etch)	22.99	0.72	21	0.72	21
Capture/Recovery (Membrane)	30.38	0.24	7	0.96	29
Catalytic Abatement	33.87	0.26	8	1.22	36
Remote Clean	38.48	1.64	49	2.86	85
Thermal Destruction	48.57	0.24	7	3.10	92

Table 44: Semiconductor Manufacture – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Plasma Abatement (etch)	22.99	1.65	21	1.65	21
Capture/Recovery (Membrane)	30.38	0.56	7	2.21	29
Catalytic Abatement	33.87	0.61	8	2.82	36
Remote Clean	38.48	3.76	49	6.58	85
Thermal Destruction	48.57	0.56	7	7.14	92

4.3. Refrigeration/Air Conditioning

Many refrigeration and air-conditioning (AC) systems use HFC refrigerants, primarily HFC 134a. During normal operation and servicing, these HFCs can be emitted into the atmosphere. Emissions also occur at equipment disposal, though HFCs are often recovered to the extent possible prior to final disposal of the refrigeration/AC equipment. Finally, emissions occur during product and equipment manufacture and from used refrigerant containers.

The refrigeration and air-conditioning sector includes the following major end-uses:

- Household refrigeration and other appliances
- Motor vehicle air-conditioning (MVAC)
- Chillers
- Retail food refrigeration
- Cold storage warehouses
- Refrigerated transport
- Industrial process refrigeration
- Residential air-conditioning
- Small commercial air-conditioning/heat pumps

Each end-use category has a unique emissions profile that is based on the equipment charge size; the HFCs used; loss rates during equipment lifetime, servicing, and disposal; and when the end-use transitioned into HFCs as a refrigerant (based on the mandated phase-out of ozone depleting substances such as CFCs and HCFCs). Additionally, each end-use category has unique market characteristics (e.g., market size and growth rate). Although each of the above end-use categories could be subdivided further based on the broad variety of refrigeration and air-conditioning equipment in use in California, the categorization chosen for this analysis captures the similarities in emission profiles and emission reduction opportunities common to each.

4.3.1. Refrigeration/AC: Baseline Emissions

Emission estimates and projections for most refrigeration and air-conditioning end-uses are based on the U.S. EPA study, *Analysis of Costs to Abate International Ozone-Depleting Substance Substitute Emissions* (EPA 2004e). This report contains aggregate emission estimates for refrigeration and air-conditioning together with information on the percent contribution to aggregate emissions for each end-use sector. The emission estimates by end-use sector were apportioned to California by either applying appropriate California to U.S. ratios or by replacing EPA (2004e) estimates with estimates provided by the CARB, depending on the end-use sector. Specifically, the following data sources were used to apportion U.S. emissions by end-use sector to California:

- **Commercial Refrigeration and Air-Conditioning:** Aggregate U.S. refrigeration and air-conditioning estimates were disaggregated into chillers, retail food refrigeration, cold storage, and commercial air-conditioning using data provided by EPA (2004e). Each of these emission estimates was multiplied by the ratio of California to U.S. commercial cooling or refrigeration energy use, as appropriate. California commercial energy consumption data were taken from the background spreadsheets of CEC (2003a) Purchased electricity estimates for U.S. commercial space cooling and refrigeration were from EIA (2005). Ratios for commercial space cooling varied annually and ranged from 10 to 12 percent; ratios for commercial refrigeration ranged from 11 to 12 percent.
- **Residential Refrigeration and Air-Conditioning:** Aggregate U.S. refrigeration and air-conditioning estimates were disaggregated into residential air-conditioning and other appliances using data provided by EPA (2004e). These emissions were apportioned to California by applying a ratio of residential air-conditioning or refrigerator/freezer units in California (CEC 2003a) relative to the United States (EIA 2004). These ratios varied by year and were approximately 7 percent for residential air-conditioning and 10 percent for residential refrigeration.
- **Industrial Process and Refrigerated Transport:** Aggregated U.S. refrigeration and air-conditioning estimates were disaggregated into these two end-uses using data provided by EPA (2004e). These emissions were apportioned to California using a ratio of 2001 state domestic product to 2001 U.S. gross domestic product (BEA 2003), which was assumed to be a constant 13 percent for all years.
- **Motor Vehicle Air-Conditioning:** Aggregate U.S. refrigeration and air-conditioning estimates were disaggregated into the motor vehicle air-conditioning end-use, using data provided by EPA (2004e). Because CARB was able to provide baseline emission estimates for this end-use for California, the disaggregated U.S. estimate was replaced with the CARB data for motor vehicle air-conditioning.

The resulting emission estimates for each end-use were then aggregated into a combined refrigeration and air-conditioning baseline for California. Information on the breakdown of emissions by end-use was used to estimate technical applicability of each mitigation option, as described in the following section. Table 45 presents baseline emission estimates.

Hydrofluorcarbon emissions from refrigeration and air-conditioning in California are expected to grow steadily from 2000 through 2020, primarily as the result of the phase-out of ozone depleting substance use in refrigeration and air-conditioning, which is being replaced mainly with HFCs.

Table 45: HFC Emission Baseline for Refrigeration and Air-Conditioning (MMTCO$_2$ Eq.)

	2000	2005	2010	2015	2020
Refrigeration/AC	5.09	9.16	14.32	19.35	24.38

However, it is important to note that this baseline analysis does not account for potential effects of future mitigation activities under the Pavley Bill. This bill, which requires the reduction of GHG emissions from motor vehicles, may cause MVAC emissions to drop. Taking into account the penetration of 2009 and later vehicles meeting the new standard into the fleet, the baseline MVAC emissions may actually be 18 percent lower by 2020.

4.3.2. Refrigeration/AC: Mitigation Options

Mitigation options for refrigeration and air-conditioning equipment target emissions of HFCs that occur during equipment operation, servicing, and disposal. The use of refrigeration and air-conditioning equipment also generates "indirect" emissions of GHGs (primarily CO_2) from the generation of power required to operate the equipment or, in the case of motor vehicle air-conditioners, from the combustion of motor gasoline. To the extent possible, both direct and indirect emissions are considered in this analysis. The information summarized in Table 46 is based on data quantified in the U.S. EPA study, *Analysis of Costs to Abate International Ozone-Depleting Substance Substitute Emissions* (EPA 2004e), and the California Air Resources Board's *Staff Report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles* (CARB 2004).

CARB (2004) was prepared in response to AB 1493, which directs the CARB to adopt regulations to achieve the maximum feasible and cost-effective reduction of GHG emissions from motor vehicles. The report evaluates options to mitigate HFC emissions from motor vehicle air-conditioners, among other GHG emission reduction options. This analysis adopts the emission reduction options and reduction potentials that were presented in CARB (2004); however, because that report did not present cost information for the individual motor vehicle air-conditioning reduction options, the present analysis relies on the most current cost data available. It is important to note that options to reduce HFC emissions from motor vehicle air-conditioners are presently being evaluated by the industry, and new information is continually being developed. Any analysis of the costs of these options should therefore be evaluated in that context. Market penetration assumptions presented in Table 46 were developed within the context of the proposed regulation, but were otherwise developed independently as discussed further below.

Table 46: Mitigation Options for Refrigeration/Air-Conditioning

Name	Description	MP Year	MP (%)	TA	RE	Capital Cost[a]	Annual Cost[a]	Benefits[a]
Improved HFC-134a in MVACs*	Improving system components to reduce charge size, leak rates, and/or system efficiency.	2010	1	15	18	404.80	-	168.30
		2020	15	12				
HFC-152a in MVACs	Replaces HFC-134a and uses improved system components.	2010	0	15	89	192.33	-	54.15
		2020	12	12				
CO_2 for New MVACs	Consistent with traditional MVAC systems with the addition of components used to handle CO_2 at high pressure levels.	2010	0	15	100	611.97	-	86.03
		2020	12	12				
Replace DX with Distributed System	Comprised of many compressors connected by a water loop to a single cooling unit.	2010	3	54	93	90.91	-	13.83
		2020	15	52				
Leak Repair	Leak reduction resulting from simple repairs to major system upgrades.	2010	3	32	95	10.89	-	6.23
		2020	5	32				
Recovery (REFRIG)	Recovery and recycling of refrigerant during equipment service and disposal.	2010	10	10	95	26.19	3.40	1.69
		2020	15	13				
Secondary Loop	Pump cold fluid to remove heat from equipment or areas to be cooled.	2010	3	54	99	43.64	-	(12.54)
		2020	15	52				
Ammonia Secondary Loop	Has excellent thermodynamic properties and strong odor (making leaks easier to detect).	2010	1	54	100	54.55	12.47	(12.54)
		2020	8	52				

MVACs = Motor Vehicle Air Conditioners; MP = Market Penetration; TA = Technical Applicability; RE = Reduction Efficiency; DX = direct expansion

[a] All costs and benefits are expressed in year 2000 $ per $MTCO_2$ Eq.

As shown in Table 46, three technology options are considered in this analysis for MVACs include: (1) improved HFC-134a systems, (2) HFC-152a systems, and (3) CO_2 systems. All options are compared to conventional HFC-134a MVACs, which are assumed to have a charge size of 951 grams,[24] a lifetime of 16 years, and average annual refrigerant emissions of 85 grams—including regular leakage, accidental losses, and losses at servicing and disposal (CARB 2004).

The improved HFC-134a systems can reduce direct emissions from regular leakage by 50 percent, due to improvements in flexible hose construction and dimensions, system component connections, and compressor shaft seals (CARB 2004). This reduced leakage translates into an estimated emission reduction of 15 grams of refrigerant per year (CARB 2004). This option is assumed to have a capital cost of approximately $45 per car (or $405 per $MTCO_2$ Eq. reduced) and to improve MVAC fuel efficiency by between 25 and 30 percent (EPA 2004e; SAE 2003). It is assumed that improved HFC-134a systems will be available in the near-term, beginning in 2009.

The use of HFC-152a as a drop-in replacement for HFC-134a can reduce total emissions by 89 percent, as a result of its lower GWP (140 for HFC-152a compared to 1,300 for HFC-134a) (SAE 2003). This option is assumed to have a capital cost of approximately $25 per car (or $192 per $MTCO_2$ Eq. reduced) and to result in a 10 percent improvement in overall fuel efficiency (EPA 2004a; SAE 2003). This alternative refrigerant may also be used in an improved "low-leak" system that would further reduce emissions—an option currently being analyzed by CARB (CARB 2004). However, because no data on capital cost are readily available for this low-leak version, only the drop-in HFC-152a system is explored in this analysis. It is assumed that this option will be available in the mid-term, beginning in 2012.

Carbon dioxide, with a GWP of only 1, can fully replace the use of HFC-134a in MVACs, thereby reducing 100 percent of HFC emissions (assumed to be 85 g per year). This option is assumed to have a capital cost of approximately $113 per car (or $612 per $MTCO_2$ Eq. reduced) and to result in improved fuel efficiencies of 20 to 25 percent (EPA 2004e; SAE 2003). ICF assumes that this option will be available in the mid-term, beginning in 2012.

For all three MVAC options, annual cost savings associated with saved refrigerant and saved gasoline are considered. Specifically, refrigerant savings—resulting from lower refrigerant replacement costs for the HFC-134a option and a lower cost of the refrigerant in the CO_2 option—are associated with improved HFC-134a and CO_2 systems, calculated assuming a cost for HFC-134a of $7.94/kg (Dupont 2004). No refrigerant cost savings are assumed for HFC-152a, as these systems leak at the same rate as conventional HFC-134a and the cost of refrigerant is assumed to be the same as HFC-134a.

All three MVAC options are associated with system efficiency improvements and, thus, savings that result from reduced gasoline consumption. Annual gasoline cost savings are based on EPA

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[24] Actual MVAC charge sizes are expected to decrease in future; however, due to uncertainty regarding future charge sizes, a charge of 951 g is assumed for all years for modeling baseline emissions and the abatement analysis. It should be noted that analyses show that smaller charge sizes do not necessarily result in lower "regular" leakage.

(2004e)—which is based on data from Rugh and Hovland (2003)—which assumes an average gasoline price of $1.74/gallon (CARB 2004). Although this analysis does not model a range of cost scenarios, it should be noted that this gasoline price may not correspond with current market conditions; for this reason, CARB is modeling an alternative cost scenario using a gasoline value of $2.30/gallon (CARB 2004). If a higher gasoline price was used in this analysis, the final costs of all three MVAC options would be lower, as the costs of these options are strongly dependent on the assumed price of gasoline.

Because there is still much uncertainty regarding future market penetrations for all of these MVAC options, it was conservatively assumed that all options will share the market evenly by 2015, and that by 2020, these alternatives will fully penetrate the *new* MVAC market. However, because it is assumed that improved HFC-134a systems will be commercialized first, this option will penetrate the largest number of vehicles by 2020. In reality, it is likely that one alternative will "win" with manufacturers, but this analysis does not attempt to predict market choices.

Three technology options are analyzed for large stationary equipment. Distributed systems, HFC secondary loop systems (SLS), and ammonia SLS were all considered for use in retail food and cold storage applications, with assumed equipment lifetimes of 20 years. Emissions avoided for each option are based on EPA (2004e), which assume emission reductions of 93 percent, 98.5 percent, and 100 percent for distributed systems, HFC SLS, and ammonia SLS, respectively. Energy consumption is also considered for these options in calculating indirect emissions and annual costs/savings. According to EPA (2004e), the distributed option results in energy savings of 8 percent, while the two secondary loop systems result in energy penalties of around 15 percent. Market penetration values are based on EPA (2004e), where distributed systems and HFC secondary loop systems are assumed to penetrate the *new* market of retail food and cold storage equipment equally, and ammonia SLS penetrates at approximately 50 percent of this rate, because of public hesitation over its use. By 2020, it is assumed that these three options will displace 80% of baseline HFC emissions from new retail food and cold storage equipment (30% penetration for distributed, 30% for HFC secondary loop systems, and 20% for ammonia SLS). It should be noted that these options can also displace emissions from existing retail food and cold storage equipment; however, because the EPA (2004e) cost analysis does not address the costs to retrofit existing systems, these options are not assumed to penetrate existing installations.

Finally, two practice options were also considered: (1) leak repair for large equipment (i.e., chillers, retail food, cold storage, industrial process refrigeration); and (2) refrigerant recovery/recycling for small equipment (i.e., refrigerated transport, household/other small appliances, commercial unitary AC, and residential AC). The leak repair option is based on cost and emission reduction estimates provided in EPA (2004e), and is considered to be applicable only for large equipment, which could require more costly repairs or equipment upgrades. The recovery/recycling option is based on IEA (2003) and is assumed to be applicable only for small equipment (excluding MVACs).[25] This is because refrigerant recovery from large equipment is

[25] This option was not applied to MVACs because more data is needed to ensure that the assumptions developed for this abatement option in IEA (2003) are consistent with the baseline emission assumptions developed by CARB. If additional information becomes available, refrigerant recovery from MVACs will be added as an option to this analysis.

assumed to be practiced in the baseline, as significant cost savings are associated with the recovery of large quantities of refrigerant. Market penetrations for these two options are based on EPA (2004e), and are assumed to be relatively low, due to existing use of these practices in the baseline. Specifically, the analysis assumes that recovery is practiced at 80% in the baseline, but that it can reach 95% penetration by 2020, if additional recovery regulations are promulgated.

Another important option for reducing refrigerant emissions is the recovery of refrigerant at equipment servicing and disposal. In particular, refrigerant losses at service may be particularly high if jobs are performed by do-it-yourselfers (DIYers), who do not have access to proper recovery equipment and other tools to reduce emissions. Likewise, emissions at disposal can also be significant if refrigerant recovery is not performed prior to vehicle scrapping. Although this option is not modeled in the analysis, due to uncertainty regarding current and potential levels of refrigerant emissions avoided through recovery and associated costs, it should be noted that discussion is ongoing to explore methods for increasing recovery efforts in the State of California.

While this analysis explores the reduction potential and costs associated with the penetration of three alternatives into new retail food and cold storage equipment, there is additional potential for emission reductions if these abatement options are applied as retrofit options into existing (in-use) equipment prior to the end of its useful life. Please see Exhibit 1 for more information.

Exhibit 1: Additional Abatement Opportunity: Replacing In-Use Stationary Equipment

This analysis explores the reduction potential and costs associated with the penetration of three alternatives into new retail food and cold storage equipment; however, there is additional potential for emission reductions if these abatement options are applied as retrofit options into existing (in-use) equipment prior to the end of its useful life. Although retrofit costs for these options would be higher than those presented in this analysis, the associated emission reductions should not be overlooked. Indeed, the replacement of existing retail food and cold storage equipment can lead to significant emission reductions, given the equipment's large charge sizes, high leak rates, and long lifetimes (which are assumed to be 20 years).

To explore the impacts of displacing baseline emissions from both new and existing stationary equipment in the retail food and cold storage end-uses, ICF conducted a sensitivity analysis. Specifically, the same market penetration values assumed for new retail food/cold storage equipment in the main analysis were applied to the entire (new and existing) retail food/cold storage baseline in the sensitivity analysis. The results, summarized in Table A below, indicate that 40% of total refrigeration/AC emissions in 2020 (9.81 MMTCO$_2$ Eq) can be abated by applying the same market penetrations to new and existing equipment—up from the 19% (4.69 MMTCO$_2$ Eq) presented in the main report, which assumes that the options are applied to only new equipment (see Table 50).

Table A: Additional Abatement Opportunities for Refrigeration

Option Name	Market Penetration		Reduction Efficiency	Reduction off Baseline (%)		Reduction (MMTCO$_2$ Eq)	
	2010	2020		2010	2020	2010	2020
Distributed System	15	30	93	7	14	1.07	3.53
Secondary Loop	15	30	99	8	15	1.13	3.74
Ammonia Secondary Loop	5	20	100	3	10	0.38	2.53
TOTAL	**35**	**80**		**18**	**40**	**2.58**	**9.81**

Note: Totals may not sum due to independent rounding.

4.3.3. Refrigeration/AC: Results

The costs and savings associated with each mitigation option were explored under the two discount rate (DR) and tax rate (TR) scenarios: (a) DR = 4%, TR = 0%, and (b) DR = 20%, TR = 40%. The break-even prices and reductions associated with these mitigation options are displayed below for years 2010 and 2020 in Table 47 through Table 50. In 2020, California could achieve 2.86 and 0.44 MMTCO$_2$ Eq. in reductions at a break-even cost equal to or less than zero, under scenarios (a) and (b), respectively.

Table 47: Refrigeration/Air-Conditioning— Emission Reductions and Break-Even Prices (Scenario a: 2010) (Year=2010, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Improved HFC-134a in MVACs	(133.56)	< 0.01	< 1	< 0.01	< 1
HFC-152a in MVACs	(37.64)	-	-	< 0.01	< 1
CO_2 for New MVACs	(33.51)	-	-	< 0.01	< 1
Replace DX with Distributed System	(6.58)	0.25	2	0.25	2
Leak Repair	(3.78)	0.13	1	0.38	3
Recovery (REFRIG)	4.94	0.14	1	0.52	4
Secondary Loop	13.97	0.26	2	0.78	5
Ammonia Secondary Loop	25.33	0.09	1	0.88	6

Table 48: Refrigeration/Air-Conditioning— Emission Reductions and Break-Even Prices (Scenario a: 2020) (Year=2020, DR=4%, TR=0%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Improved HFC-134a in MVACs	(133.56)	0.07	< 1	0.07	< 1
HFC-152a in MVACs	(37.64)	0.30	1	0.37	2
CO2 for New MVACs	(33.51)	0.34	1	0.71	3
Replace DX with Distributed System	(6.58)	1.79	7	2.50	10
Leak Repair	(3.78)	0.37	2	2.86	12
Recovery (REFRIG)	4.94	0.44	2	3.30	14
Secondary Loop	13.97	1.90	8	5.20	21
Ammonia Secondary Loop	25.33	1.01	4	6.20	25

Table 49: Refrigeration/Air-Conditioning – Emission Reductions and Break-Even Prices (Scenario b: 2010) (Year=2010, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Improved HFC-134a in MVACs	(42.52)	< 0.01	< 1	< 0.01	< 1
Leak Repair	(1.61)	0.13	1	0.14	1
HFC-152a in MVACs	5.61	-	-	0.14	1
Recovery (REFRIG)	10.37	0.14	1	0.28	2
Replace DX with Distributed System	14.09	0.25	2	0.52	4
Secondary Loop	25.57	0.26	2	0.78	5
Ammonia Secondary Loop	41.03	0.09	1	0.88	6
CO_2 for New MVACs	104.12	-	-	0.88	6

Table 50: Refrigeration/Air-Conditioning – Emission Reductions and Break-Even Prices (Scenario b: 2020) (Year=2020, DR=20%, TR=40%)

Option	Break-Even Price ($/MTCO$_2$ Eq.)	Incremental Reductions		Sum of Reductions	
		MMTCO$_2$ Eq.	% of Baseline	MMTCO$_2$ Eq.	% of Baseline
Improved HFC-134a in MVACs	(42.52)	0.07	< 1	0.07	< 1
Leak Repair	(1.61)	0.37	2	0.44	2
HFC-152a in MVACs	5.61	0.30	1	0.74	3
Recovery (REFRIG)	10.37	0.44	2	1.18	5
Replace DX with Distributed System	14.09	1.79	7	2.97	12
Secondary Loop	25.57	1.90	8	4.86	20
Ammonia Secondary Loop	41.03	1.01	4	5.87	24
CO_2 for New MVACs	104.12	0.34	1	6.20	25

5.0 Conclusions and Recommendations

The results of this study show that a number of cost-effective mitigation options have the potential to reduce non-CO_2 greenhouse gas emissions in California. Overall, this study analyzed 59 mitigation options in seven source categories. The results are presented in two sections: Scenario A presents the results for a 4 percent discount rate and a 0 percent tax rate, while Scenario B presents the results for a 20 percent discount rate and a 40 percent tax rate. Results for 2010 and 2020 are discussed for both scenarios. Overall, costs were lower for Scenario A, as would be expected with lower discount and tax rates. However, differences in cumulative reductions varied widely at select break-even prices.

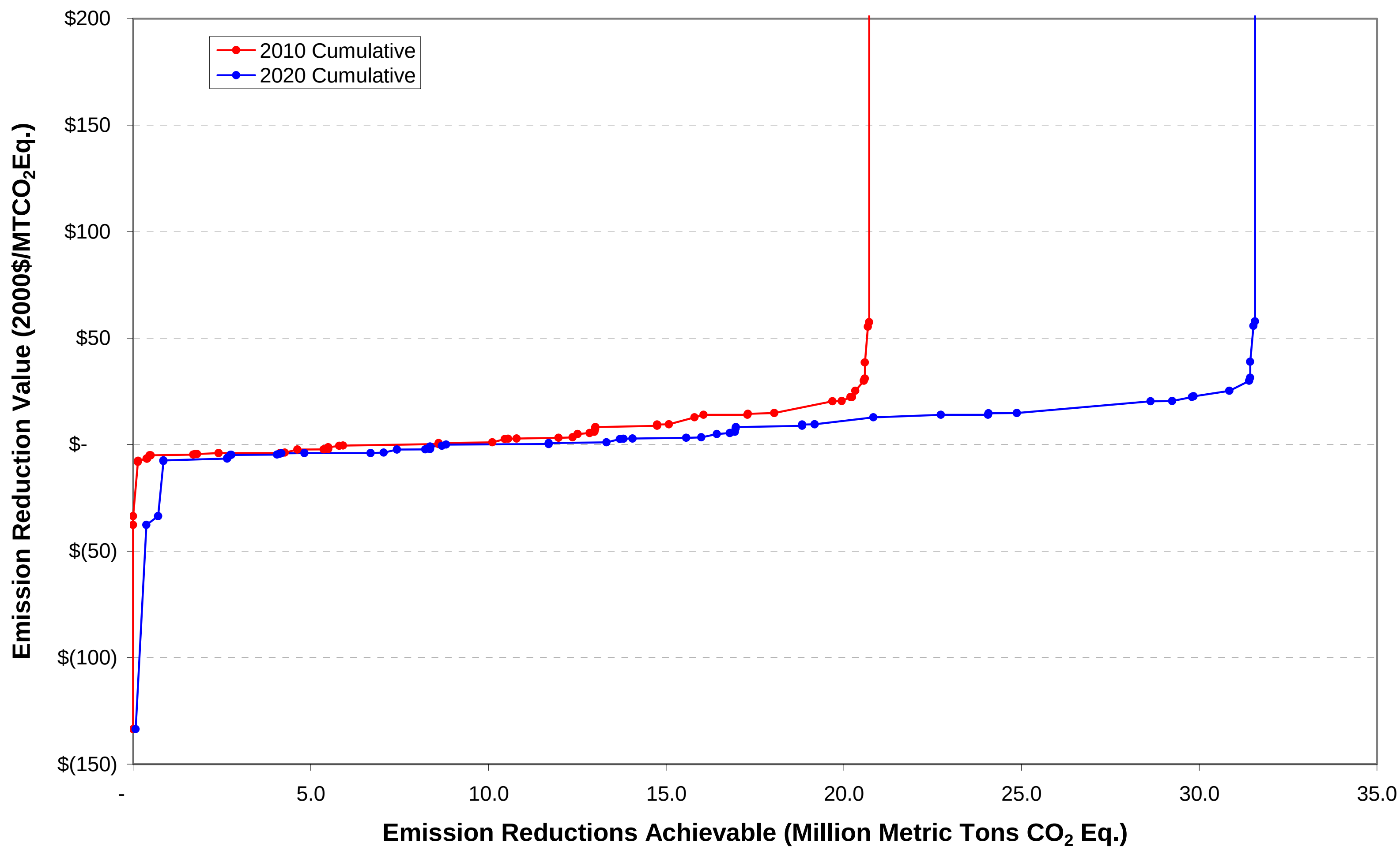
In aggregate, options in this analysis have the potential to reduce 20.7 $MMTCO_2$ Eq. in 2010, and 31.6 $MMTCO_2$ Eq. in 2020. In comparison, the non-CO_2 baseline emissions for the sources examined in this study[26] are projected to be 40.7 $MMTCO_2$ Eq. and 57.2 $MMTCO_2$ Eq., respectively. Thus, the potential reductions represent over half of the baseline emissions—51 percent of total emissions in 2010, and 55 percent of emissions in 2020. Landfills present the greatest opportunity for emission reductions, at 9.0 $MMTCO_2$ Eq. for 2010 and 9.7 $MMTCO_2$ Eq. in 2020. In 2010, significant reductions can also be achieved in manure management (5.8 $MMTCO_2$ Eq.) and semiconductor manufacturing (3.1 $MMTCO_2$ Eq.). In 2020, significant reductions can be achieved in semiconductor manufacturing (7.1 $MMTCO_2$ Eq.), manure management (6.2 $MMTCO_2$ Eq.), and refrigeration/AC (6.2 $MMTCO_2$ Eq.). Although sizeable reductions of emissions from semiconductor manufacturing are possible, the majority of these reductions are available at greater than \$20/$MTCO_2$ Eq.

5.1. Scenario A: 4 Percent Discount Rate/0 Percent Tax Rate

Figure 1 illustrates the cumulative marginal abatement costs curves (MACC) for 2010 and 2020, assuming a discount rate of 4 percent and a tax rate of 0 percent. Several of the technologies and measures investigated represent highly cost-effective options for reducing emissions; in fact, they are anticipated to result in a net cost savings, exclusive of any additional incentives to reduce emissions. Cost-saving options exist for natural gas systems, landfills, manure management, and refrigeration/AC, and can be identified by their negative break-even prices. In total, these options represent 5.9 $MMTCO_2$ Eq. of potential reductions in 2010, and 8.7 $MMTCO_2$ Eq. in 2020. These savings are largely possible due to increases in efficiency, energy savings, or energy recovery associated with implementation. Options for reducing emissions from landfills and manure management account for 86 percent of these reductions. As these options generate more revenue than they would cost over the time frame in this analysis, their implementation should be considered regardless of GHG benefits. Possible reasons that these options have not yet been implemented include informational and regulatory barriers.

[26] Note that these baseline estimates do not represent all projected emissions in California, and may overestimate emissions for some sources. Please see Section 2.1 for more information.

Figure 1: MACC for Non-CO_2 Emissions in California, DR= 4 percent and TR= 0 percent



For a break-even price of less than \$20/MTCO_2 Eq., an additional 12.1 MMTCO_2 Eq. can be reduced in 2010, and 16.2 MMTCO_2 Eq. in 2020. Options for abating landfill CH_4 emissions account for the bulk of this potential, representing 56 percent and 45 percent of possible reductions in 2010 and 2020. In total, by implementing all options with a break-even price of less than \$20/MTCO_2 Eq., 18.0 MMTCO_2 Eq. can be reduced in 2010, and 24.9 MMTCO_2 Eq. in 2020. At \$50/MTCO_2 Eq., nearly all of the options included in this analysis can be implemented. At this level, cumulative reductions of 20.6 MMTCO_2 Eq. in 2010 and 31.4 MMTCO_2 Eq. in 2020 are estimated. Figure 2 and Figure 3 illustrate the achievable emission reductions for each source at these break-even prices in 2010 and 2020, respectively.

Two options—installing an electricity project at landfills with WIP greater than 1 million tons, and installing a covered lagoon at a large dairy operation (not considering lagoon cost)—represent 20 percent of potential reductions and could be implemented at a relatively low cost. These lagoon projects have a break-even price of -\$3.94/MTCO_2 Eq., while the break-even price of the landfill electricity projects is \$0.26/MTCO_2. The magnitude of these reductions is possible due to the substantial amount of CH_4 emitted from these large landfills and dairy operations.

By examining the areas below and above the curves, the total amount of emission reductions that could be achieved with a net sum cost of zero can be estimated. Specifically, this value can be found by identifying the point at which total net savings equals net costs. Net savings can be estimated by calculating the area bounded by the x-axis and points on the curve at which cost is *less than* \$0/MTCO_2 Eq. Next, net costs are estimated by calculating the area bounded by the x-axis and points on the curve at which cost is *more than* \$0/MTCO_2 Eq., up until the point at which net costs equal net savings. Figure 4 illustrates the location of this point on the MACC for 2010. For 2010, 36 mitigation options could be implemented until this point (the break-even price at this point is about \$8/MTCO_2) with a total emission reduction of greater than 13 MMTCO_2 Eq.[27] For 2020, 56 mitigation options could be implemented until this point (at which the break-even price is about \$22/MTCO_2), with total emission reductions of 21 MMTCO_2 Eq.

An important part of any MACC analysis is to identify points on the curve before a drastic increase in break-even price. Recognition of these points can help policymakers decide which suite of options can be implemented with a relatively low net cost per reduction. In 2010, 20.0 MMTCO_2 Eq. can be reduced by implementing all options at or below \$20.45/MTCO_2 Eq., at which point, the curve turns steeply upward. In 2020, 31.4 MMTCO_2 Eq. can be reduced by implementing options at or below \$31.37/MTCO_2 Eq. At break-even prices slightly below these levels, a significant amount of potential reductions are lost for very little difference in cost. At break-even prices somewhat above these levels, relatively small amounts of additional reductions can be achieved.

[27] The point on the MACC where net cost is zero is actually around 14 MMTCO_2 Eq., as shown in Figure 4. However, this point occurs in between mitigation options; therefore this study assumes that only about 13 MMTCO_2 Eq. can be reduced with a net cost of zero or less; as additional options are implemented, costs will begin to outweigh cost savings.

Figure 2: Achievable emissions reductions (MMTCO2 Eq.) for all sources in 2010 (DR= 4 percent and TR= 0 percent)

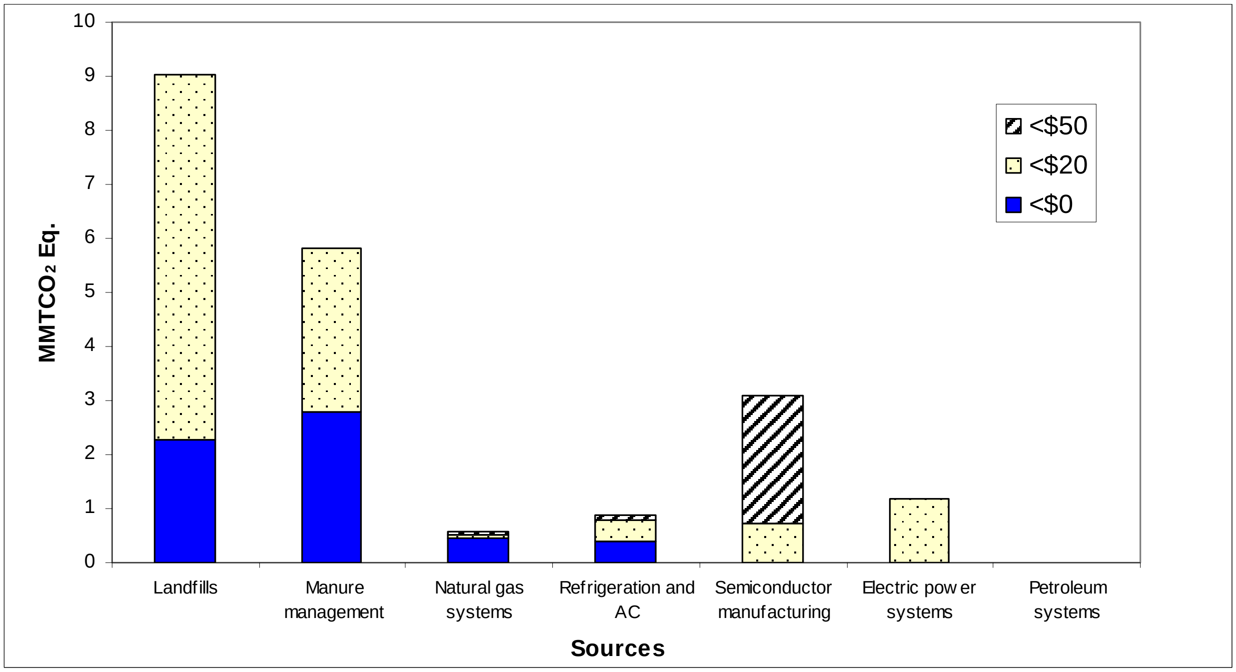


Figure 3: Achievable emissions reductions (MMTCO$_2$ Eq.) for all sources in 2020 (DR= 4 percent and TR= 0 percent)

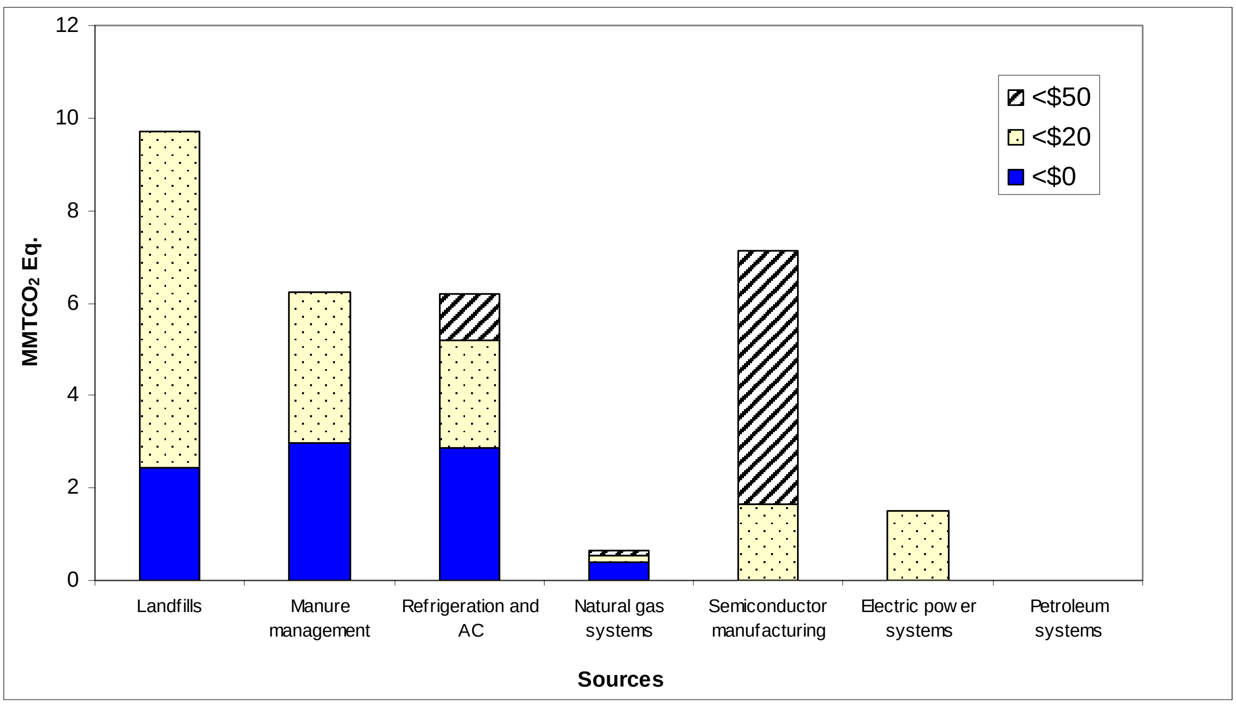


Figure 4: MACC for California in 2010, Cumulative Reductions Available for Zero Net Cost (DR=4%,TR=0%)

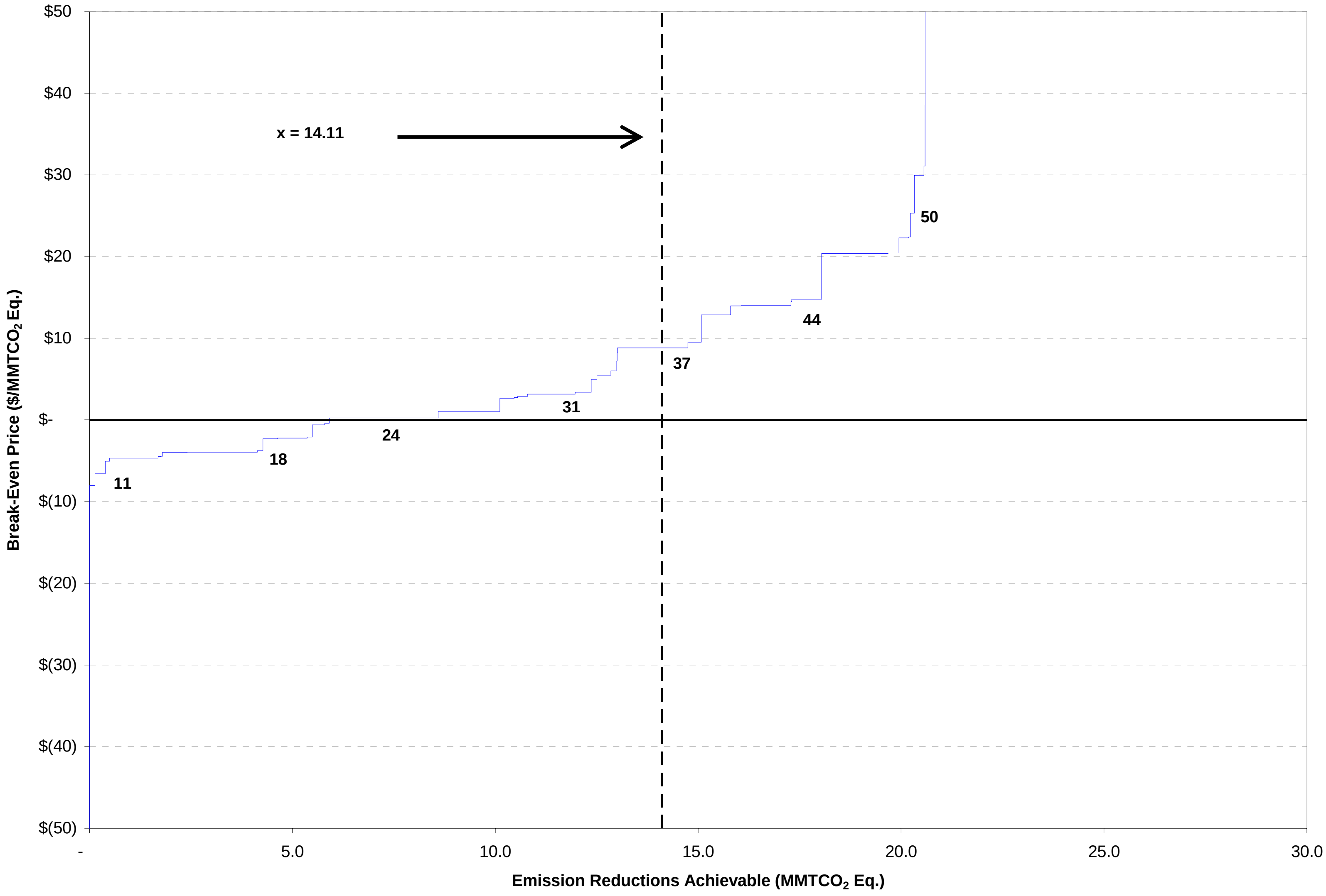


Figure 4: (continued)

Mitigations Options Represented (4% DR, 0% TR)

1.Improved HFC-134a in MVACs (Refrigeration & AC)
2.HFC-152a in MVACs (Refrigeration & AC)
3.CO2 for New MVACs (Refrigeration & AC)
4.P&T-Fuel Gas Retrofit for BD Valve (Natural Gas)
5.P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission (Natural Gas)
6.Replace DX with Distributed System (Refrigeration & AC)
7.P&T-D I&M (Compressor Stations) (Natural Gas)
8.Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) (Natural Gas)
9.Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Natural Gas)
10.P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Natural Gas)
11.Direct Gas Use - WIP 1 Million+ (Solid Waste)
12.C-Altering start-up Procedures During Maintenance (Natural Gas)
13.D-D I&M (Distribution) (Natural Gas)
14.Direct Gas Use - WIP < 1 Million (Solid Waste)
15.Covered Lagoon, not including Lagoon - Large Dairy (Manure Management)
16.Leak Repair (Refrigeration & AC)
17.Direct Gas Use - WIP < 500,000 (Solid Waste)
18.Covered Lagoon including Lagoon Cost - Large Dairy (Manure Management)
19.Direct Gas Use - WIP < 400,000 (Solid Waste)
20.Direct Gas Use - WIP < 300,000 (Solid Waste)
21.P&T-Installation of Flash Tank Separators Transmission & Storage) (Natural Gas)
22.Plug Flow Digester - Medium Dairy (Manure Management)
23.D-Electronic Monitoring at Large Surface Facilities (Natural Gas)
24.Electricity - WIP 1 Million+ (Solid Waste)
25.Direct Gas Use - WIP < 200,000 (Solid Waste)
26.Electricity - WIP < 1 Million (Solid Waste)
27.Electricity - WIP < 500,000 (Solid Waste)
28.2-Stage Plug Flow Digester - Large Dairy (Manure Management)
29.Electricity - WIP < 400,000 (Solid Waste)
30.Leak Reduction and Recovery (Electric Power)
31.Electricity - WIP < 300,000 (Solid Waste)
32.Recovery (REFRIG) (Refrigeration & AC)
33.Electricity - WIP < 200,000 (Solid Waste)
34.Complete Mix Digester - Medium Dairy (Manure Management)
35.P&T-Recip Compressor Rod Packing (Static-Pac) (Natural Gas)
36.Option for Flared Gas (Petroleum)
37.Covered Lagoon, not including Lagoon Cost - Small Dairy (Manure Management)
38.Direct Gas Use - WIP < 100,000 (Solid Waste)
39.Centralized Digester (Manure Management)
40.Plasma Abatement (etch) (Semiconductors)
41.Secondary Loop (Refrigeration & AC)
42.Electricity - WIP < 100,000 (Solid Waste)
43.Prod-Installation of Flash Tank Separators (Production) (Natural Gas)
44.Covered Lagoon including Lagoon Cost - Small Dairy (Manure Management)
45.Remote Clean (Semiconductors)
46.Catalytic Abatement (Semiconductors)
47.Capture/Recovery (Membrane) (Semiconductors)
48.P&T-Portable Evacuation Compressor for Pipeline Venting (Natural Gas)
49.Prod-Portable Evacuation Compressor for Pipeline Venting (Natural Gas)
50.Ammonia Secondary Loop (Refrigeration & AC)
51.Thermal Destruction (Semiconductors)
52.Prod-D I&M (Pipeline Leaks) (Natural Gas)
53.P&T-D I&M (Wells: Storage) (Natural Gas)
54.Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only) (Natural Gas)
55.P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission) (Natural Gas)
56.Prod-Installing Plunger Lift Systems In Gas Wells (Natural Gas)
57.P&T-D I&M (Pipeline: Transmission) (Natural Gas)
58.P&T-Surge Vessels for Station/Well Venting (Natural Gas)
59.Prod-Surge Vessels for Station/Well Venting (Natural Gas)

5.2. Scenario B: 20 Percent Discount Rate/ 40 Percent Tax Rate

Figure 5 illustrates the cumulative MACCs for 2010 and 2020 assuming a discount rate of 20 percent and a tax rate of 40 percent. Several of the technologies and measures investigated represent highly cost-effective options for reducing emissions; in fact, they are anticipated to result in a net cost savings, exclusive of any additional incentives to reduce emissions. Cost-saving options exist for natural gas systems, landfills, manure management, and refrigeration/AC, and can be identified by their negative break-even price. In total, these options represent 1.7 MMTCO_2 Eq. of potential reductions in 2010, and 2.1 MMTCO_2 Eq. in 2020. These savings are largely possible because of increases in efficiency, energy savings, or energy recovery associated with implementation. Options for reducing emissions from landfills account for the majority (70 percent and 60 percent, respectively) of these reductions. Because these options generate more revenue than they would cost over the time frame in this analysis, their implementation should be considered regardless of GHG benefits. Possible reasons that these options have not yet been implemented include informational and regulatory barriers.

For a break-even price of less than \$20/MTCO_2 Eq., an additional 10.8 MMTCO_2 Eq. can be reduced in 2010, and 13.9 MMTCO_2 Eq. in 2020. Once again, options for abating landfill emissions account for the bulk of this potential, representing over 58 percent and 48 percent of possible reductions in 2010 and 2020. In total, by implementing all options with a break-even price of less than \$20/MTCO_2 Eq., 12.4 MMTCO_2 Eq. can be reduced in 2010, and 16.0 MMTCO_2 Eq. in 2020. At \$50/MTCO_2 Eq., nearly all of the options included in this analysis can be implemented. At this level, cumulative reductions of 18.6 MMTCO_2 Eq. in 2010 and 28.9 MMTCO_2 Eq. in 2020 are estimated. Figure 6 and Figure 7 illustrate the achievable emission reductions for each source at these break-even prices in 2010 and 2020, respectively.

By examining the areas below and above the curves, the total amount of emission reductions that could be achieved with a net sum cost of zero can be estimated. Specifically, this value can be found by identifying the point at which total net savings equals net costs. Net savings can be estimated by calculating the area bounded by the x-axis and points on the curve at which cost is *less than* \$0/MTCO_2 Eq. Next, net costs are estimated by calculating the area bounded by the x-axis and points on the curve at which cost is *more than* \$0/MTCO_2 Eq., up until the point at which net cost equals net savings. For 2010, 12 mitigation options could be implemented until this point (the break-even price at this point is just over \$1/MTCO_2) with a total emission reduction more than 2 MMTCO_2 Eq.[28] Figure 8 illustrates the location of this point on the MACC. For 2020, 12 mitigation options could be implemented until this point (at about the same break-even price) with total emission reductions of almost 3 MMTCO_2 Eq.

As mentioned in Section 5.1, it is useful to identify points on the MACC before a drastic increase in break-even price. Recognition of these points can help policymakers decide which suite of options can be implemented with a relatively low net cost per reduction. In 2010, 10.9 MMTCO_2 Eq. can be reduced by implementing all options below \$11.48/MTCO_2 Eq., at which point, the

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[28] The point on the MACC where net cost is zero is actually close to 3 MMTCO_2 Eq. as shown in Figure 8. However, this point occurs in between mitigation options; therefore ICF considers that only about 2 MMTCO_2 Eq. can be reduced with a net cost of zero or less; implementation of additional options result in positive net costs.

curve turns steeply upward. In 2020, 15.0 MMTCO_2 Eq. can be reduced by implementing options below $14.09/MT$CO_2$ Eq. A similar point exists at $39.05/MT$CO_2$ Eq. At break-even prices slightly below these levels, a significant amount of potential reductions are lost for very little decrease in cost. At break-even prices somewhat above these levels, relatively small amounts of additional reductions can be achieved.

5.3. Recommendations

The results of this study indicate that several sources of non-CO_2 emissions in California offer significant opportunities for reducing emissions. To fully capitalize on these opportunities, the state may need to take these results one step further by conducting analyses based on additional state-specific data for sources that hold the most promise. Several of the inputs to this analysis are based on national figures that have been adjusted to reflect circumstances in California. To ensure that specific mitigation actions will deliver reductions at the costs estimated in this study, the state may want to develop or expand upon "bottom up" emission and cost data for specific sites or projects in California.

In addition, the range of mitigation opportunities addressed in this study could be expanded to include other sources of non-CO_2 emissions. For example, inclusion of nitrous oxide emissions from fertilizer application will depend on the development of process-based models to predict emissions associated with various application rates and methods. This study could be expanded to evaluate the impact of alternate policy outcomes that may increase or decrease costs and benefits of specific mitigation options (e.g., impacts of net metering on manure management options). Finally, there are some new mitigation strategies for which preliminary cost and emission reduction information could be used to further reduce emissions from certain sources (e.g., use of CO_2 in stationary refrigeration equipment).

Figure 5: MACC for Non-CO_2 Emissions in California (DR= 20 percent and TR= 40 percent)

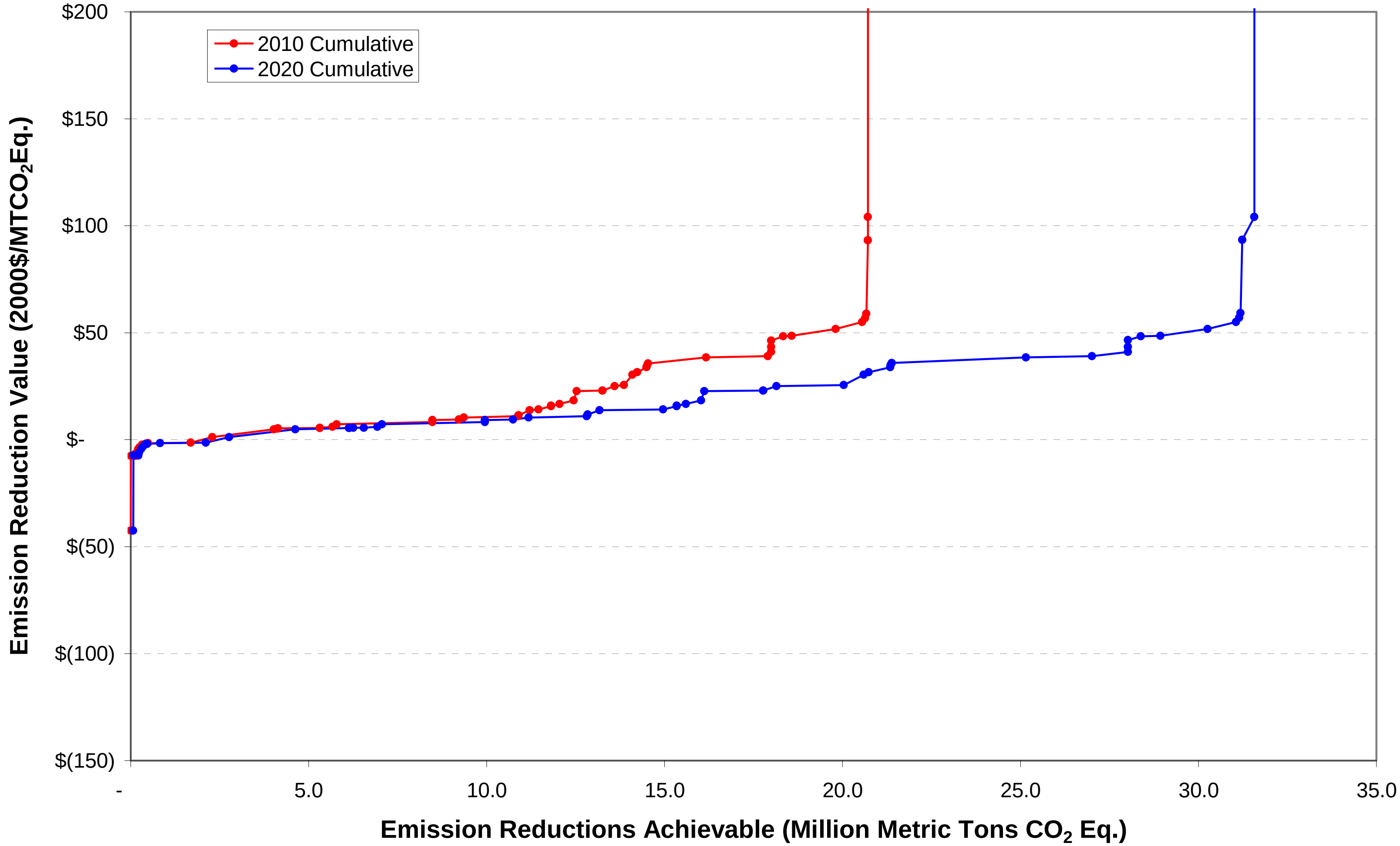

Figure 6: Achievable emissions reductions (MMTCO$_2$ Eq.) for all sources in 2010 (DR= 20 percent and TR= 40 percent)

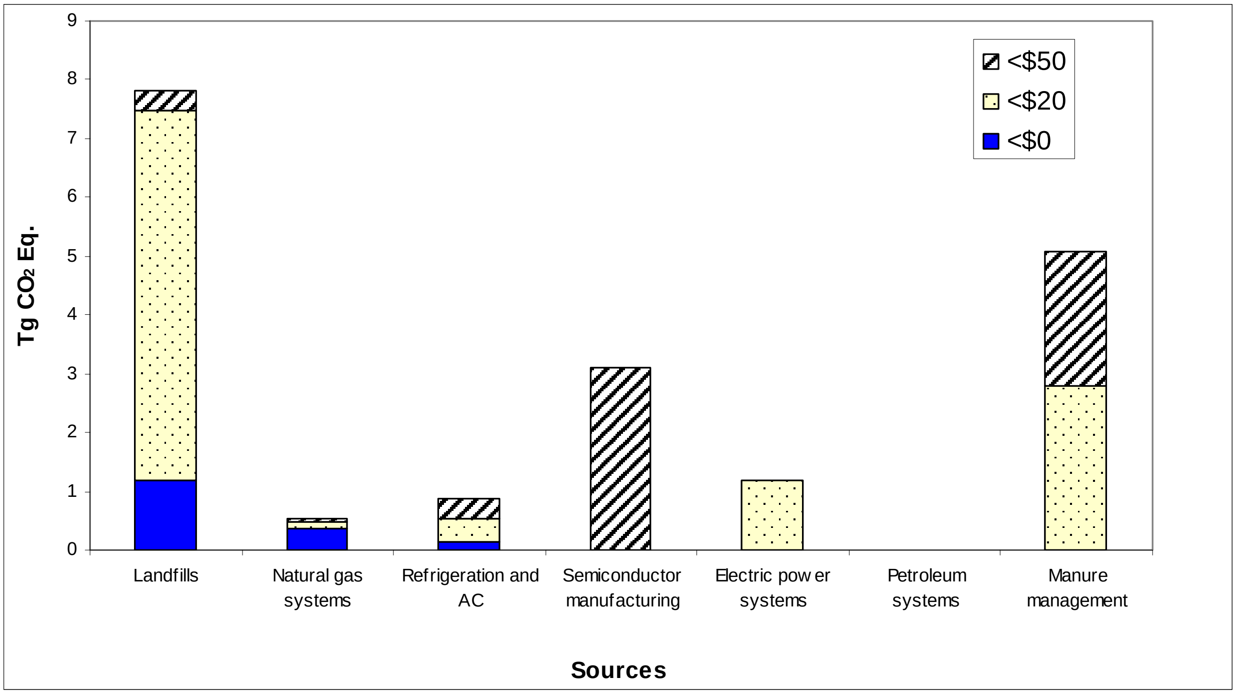

Figure 7: Achievable emissions reductions (MMTCO$_2$ Eq.) for all sources in 2020 (DR= 20 percent and TR= 40 percent)

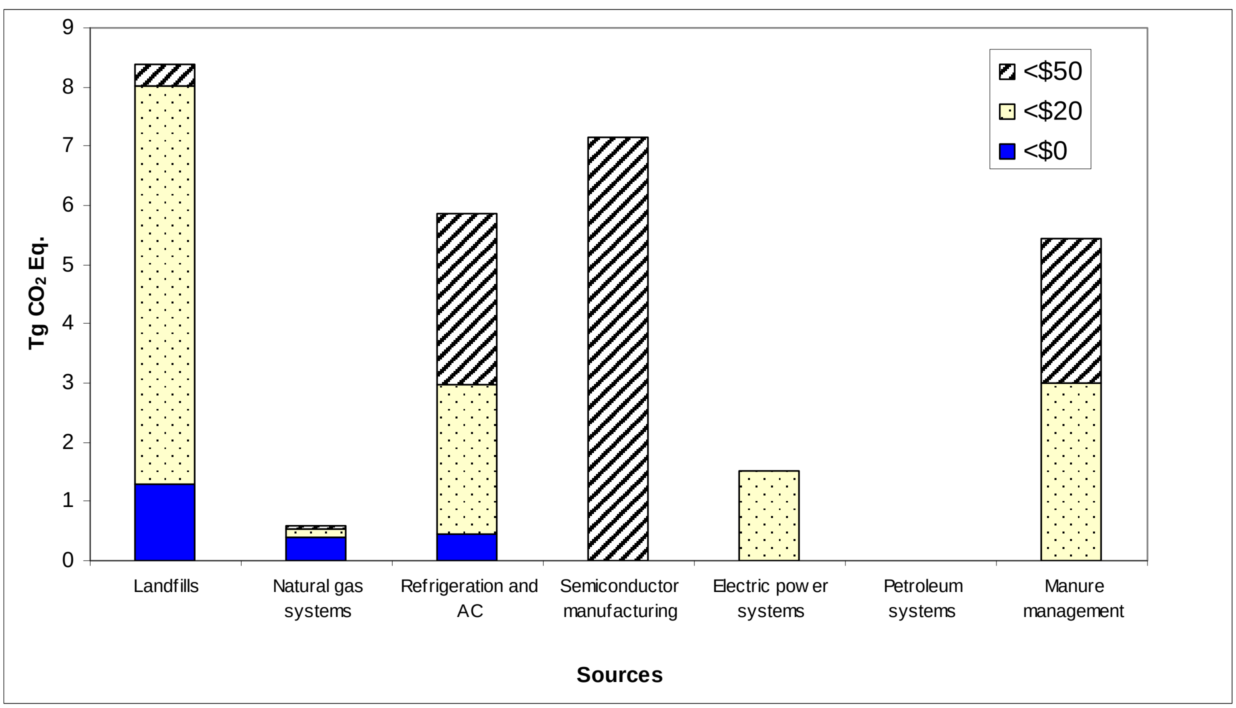

Figure 8: MACC for California in 2010, Cumulative Reductions Available for Zero Net Cost (DR=20%, TR=40%)

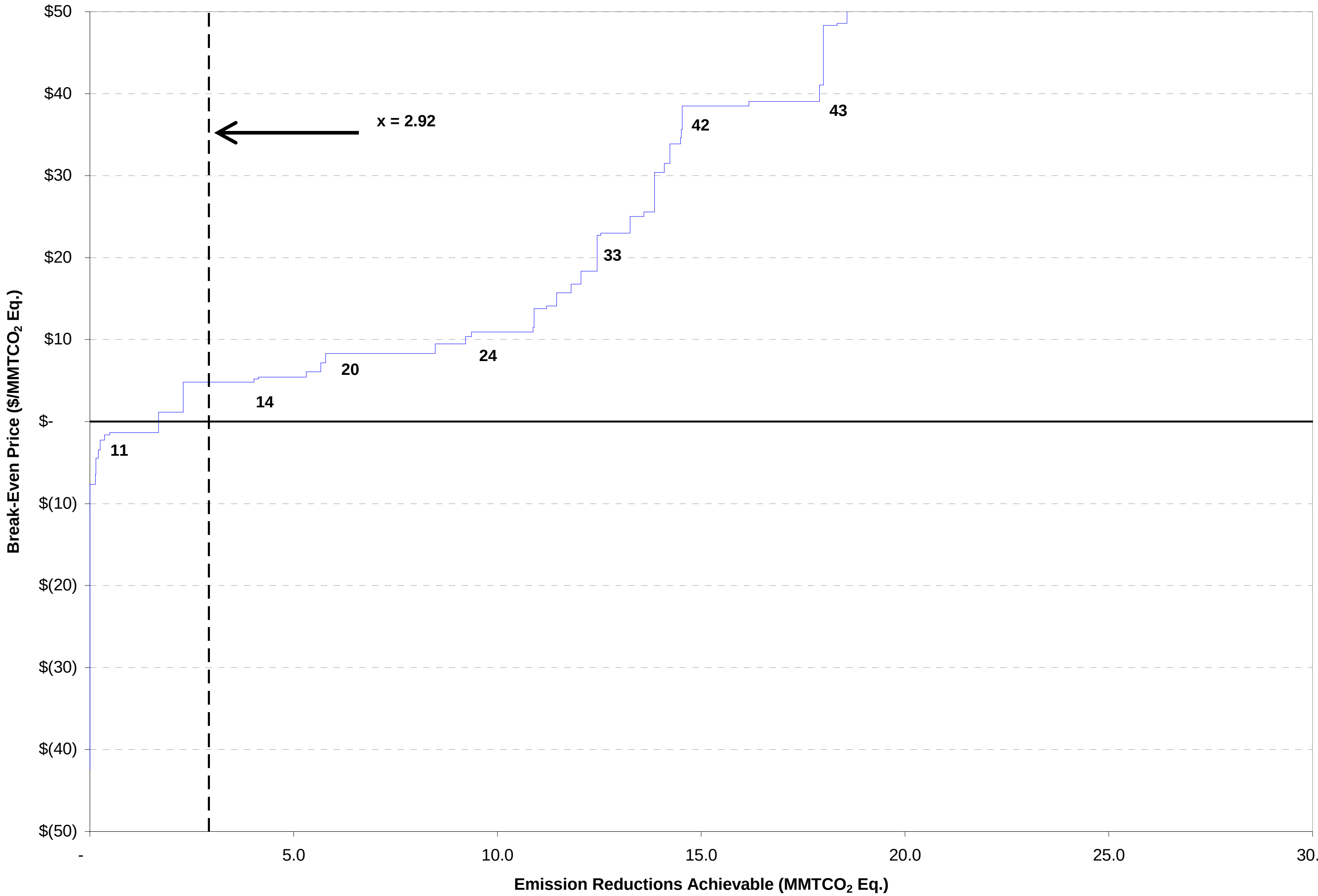

Figure 8: (continued)

Mitigations Options Represented (20% DR, 40% TR)

1.Improved HFC-134a in MVACs (Refrigeration & AC)
2.P&T-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) - Transmission (Natural Gas)
3.P&T-Fuel Gas Retrofit for BD Valve (Natural Gas)
4.Prod-Reducing the glycol circulation rates in dehydrators (not applicable to Kimray pumps) (Natural Gas)
5.P&T-D I&M (Compressor Stations) (Natural Gas)
6.C-Altering start-up Procedures During Maintenance (Natural Gas)
7.D-D I&M (Distribution) (Natural Gas)
8.Prod-Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Natural Gas)
9.P&T-Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Natural Gas)
10.Leak Repair (Refrigeration & AC)
11.Direct Gas Use - WIP 1 Million+ (Solid Waste)
12.Direct Gas Use - WIP < 1 Million (Solid Waste)
13.Covered Lagoon, not including Lagoon - Large Dairy (Manure Management)
14.D-Electronic Monitoring at Large Surface Facilities (Natural Gas)
15.P&T-Installation of Flash Tank Separators Transmission & Storage) (Natural Gas)
16.Leak Reduction and Recovery (Electric Power)
17.HFC-152a in MVACs (Refrigeration & AC)
18.Direct Gas Use - WIP < 500,000 (Solid Waste)
19.Direct Gas Use - WIP < 400,000 (Solid Waste)
20.Electricity - WIP 1 Million+ (Solid Waste)
21.Direct Gas Use - WIP < 300,000 (Solid Waste)
22.Covered Lagoon including Lagoon Cost - Large Dairy (Manure Management)
23.Recovery (REFRIG) (Refrigeration & AC)
24.Electricity - WIP < 1 Million (Solid Waste)
25.P&T-Recip Compressor Rod Packing (Static-Pac) (Natural Gas)
26.Plug Flow Digester - Medium Dairy (Manure Management)
27.Replace DX with Distributed System (Refrigeration & AC)
28.Electricity - WIP < 500,000 (Solid Waste)
29.Direct Gas Use - WIP < 200,000 (Solid Waste)
30.Electricity - WIP < 400,000 (Solid Waste)
31.Electricity - WIP < 300,000 (Solid Waste)
32.2-Stage Plug Flow Digester - Large Dairy (Manure Management)
33.Plasma Abatement (etch) (Semiconductors)
34.Option for Flared Gas (Petroleum)
35.Electricity - WIP < 200,000 (Solid Waste)
36.Secondary Loop (Refrigeration & AC)
37.Capture/Recovery (Membrane) (Semiconductors)
38.Complete Mix Digester - Medium Dairy (Manure Management)
39.Catalytic Abatement (Semiconductors)
40.Prod-Installation of Flash Tank Separators (Production) (Natural Gas)
41.Prod-D I&M (Pipeline Leaks) (Natural Gas)
42.Remote Clean (Semiconductors)
43.Covered Lagoon, not including Lagoon Cost - Small Dairy (Manure Management)
44.Ammonia Secondary Loop (Refrigeration & AC)
45.Direct Gas Use - WIP < 100,000 (Solid Waste)
46.P&T-D I&M (Wells: Storage) (Natural Gas)
47.Centralized Digester (Manure Management)
48.Thermal Destruction (Semiconductors)
49.Electricity - WIP < 100,000 (Solid Waste)
50.Covered Lagoon including Lagoon Cost - Small Dairy (Manure Management)
51.Prod-Replace High-bleed pneumatic devices with compressed air systems (Production Only) (Natural Gas)
52.P&T-Replace High-bleed pneumatic devices with compressed air systems (Transmission) (Natural Gas)
53.P&T-Portable Evacuation Compressor for Pipeline Venting (Natural Gas)
54.Prod-Portable Evacuation Compressor for Pipeline Venting (Natural Gas)
55.CO2 for New MVACs (Refrigeration & AC)
56.Prod-Installing Plunger Lift Systems In Gas Wells (Natural Gas)
57.P&T-D I&M (Pipeline: Transmission) (Natural Gas)
58.P&T-Surge Vessels for Station/Well Venting (Natural Gas)
59.Prod-Surge Vessels for Station/Well Venting (Natural Gas)

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7.0 Glossary

APCD (Air Pollution Control District): A county agency with authority to regulate stationary, indirect, and area sources of air pollution (e.g., power plants, highway construction, and housing developments) within a given county, and governed by a district air pollution control board composed of the elected county supervisors.

AQMD (Air Quality Management District): A group of counties or portions of counties, or an individual county specified in law with authority to regulate stationary, indirect, and area sources of air pollution within the region and governed by a regional air pollution control board comprised mostly of elected officials from within the region.

BACT (Best Available Control Technology): The most up-to-date methods, systems, techniques, and production processes available to achieve the greatest feasible emission reductions for given regulated air pollutants and processes.

CAFO (Concentrated Animal Feeding Operations): An animal feeding operation greater than 1,000 animal units. If certain conditions exist, animal feeding operations between 300 and 1,000 animal units can be considered a concentrated animal feeding operation.

CARB (California Air Resources Board): Gathers air quality data for the State of California, ensures the quality of this data, designs and implements air models, and sets ambient air quality standards for the state.

CARB Database: A compilation of emission estimates reported by California's 35 local air districts.

C_2F_6 (Hexafluoroethane): A greenhouse gas with a global warming potential 9,200 times that of carbon dioxide.

C_3F_8 (Octafluoropropane): A greenhouse gas with a global warming potential 7,000 times that of carbon dioxide.

C_4F_8 (Octafluorocyclobutane): A greenhouse gas with a global warming potential 8,700 times that of carbon dioxide.

CF_4 (Tetrafluoromethane): A greenhouse gas with a global warming potential 6,500 times that of carbon dioxide.

CH_4 (Methane): A greenhouse gas with a global warming potential 21 times that of carbon dioxide.

GHG (Greenhouse Gas): Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GWP (Global Warming Potential): The ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide.

HFC-23 (Trifluoromethane): A greenhouse gas with a global warming potential 11,700 times that of carbon dioxide.

LFGTE (Landfill gas-to-energy systems): Systems that capture and convert landfill gases into an energy source.

MACC (Marginal Abatement Cost Curve): Shows the total emission reductions achievable at increasing monetary values of carbon.

NF_3 (Nitrogen Trifluoride): A greenhouse gas with a global warming potential 8,000 times that of carbon dioxide.

LMOP (Landfill Methane Outreach Program): A voluntary assistance and partnership program that promotes the use of landfill gas as a renewable, green energy source.

ROG (Reactive Organic Gases): Emissions of reactive organic hydrocarbons.

Sulfur Hexafluoride: A greenhouse gas with a global warming potential 23,900 times that of carbon dioxide.

TOG (Total Organic Gases): Emissions of both reactive and non-reactive hydrocarbons.

$MMTCO_2$ Eq. (Million Metric Tons of Carbon Dioxide Equivalent): A metric measure that expresses emissions of greenhouse gases in terms of a similar amount of carbon dioxide, based on global warming potentials.

WIP (Waste in Place): Quantity of waste present in a landfill.